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Original Research

Quadriceps and Hamstrings Activation Peaks Earlier as Athletes Repeatedly Hop, but There are Differences Depending on ACL Reconstruction Technique.

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Background

After Anterior Cruciate Ligament Reconstruction (ACLR) athletes face the challenge of regaining their previous competitive level while avoiding re-injury and early knee joint cartilage degeneration. Quadriceps and hamstrings strength reductions and neuromuscular alterations potentially related to risk of re-injury are present after ACLR and relate to deficits in muscle activation.

Design

Cross-sectional laboratory study

Purpose

To examine quadriceps and hamstrings muscle activation during repeated hops in healthy pivoting-sport athletes and those who had undergone ACLR (bone-tendon-bone and semitendinosus graft) who had met functional criteria allowing return to training.

Methods

Surface electromyography (SEMG) was recorded from vastus medialis and lateralis and medial and lateral hamstrings bilaterally during 30 seconds' repeated hopping in male athletes on average eight months after ACLR surgery (5-12 months). All patients underwent hamstring (HS) (n=24) or bone-tendon-bone (BTB) reconstruction (n=20) and were compared to healthy controls (n=31). The SEMG signals were normalized to those obtained during maximal voluntary isometric contraction.

Results

A significant time shift in peak muscle activation (earlier) was seen for: vastus medialis and vastus lateralis activation in the control group, in the BTB group's healthy (but not injured) leg and both legs of the HS group. A significant time shift in peak muscle activation was seen for lateral hamstrings (earlier) in all but the BTB group's injured leg and the medial hamstrings in the control group only. Lower peak activation levels of the vastus lateralis ($p<0.001$) and vastus medialis ($p<0.001$) were observed in the injured compared to healthy legs and lower peak lateral hamstrings activity ($p<0.009$) in the injured leg compared to control leg. Decline in medial hamstring peak activation ($p<0.022$) was observed between 1st and 3rd phase of the hop cycle in all groups.

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Conclusion

Repeated hop testing revealed quadriceps and hamstring activation differences within ACLR athletes, and compared to healthy controls, that would be missed with single hop tests.

Level of evidence

3

INTRODUCTION

Athletes having surgery after anterior cruciate ligament (ACL) injury expect to return to sport with more than 90% of previous injury level capacity[1] yet only 55-60 % will return to their previous competitive level.[2] Additionally, those undergoing ACL reconstruction (ACLR) have a higher risk of reinjury[3] and osteoarthritis[4] and show worse subsequent performance and career duration.[5] Reasons for reduced participation and impaired performance are complex[6] and while results from return to sport (RTS) testing after ACLR can be useful to estimate the athlete's readiness to participate in sports,[7] clinical testing methods often used as a measure of lower limb function do not always identify specific local impairments[8] likely due to compensatory strategies[9] which suggests alternative RTS evaluations might be required.[7]

Surface electromyographical (SEMG) analysis can help identify alterations in neuromuscular control, however this is rarely used in RTS assessment.[10] While ACLR patients demonstrate continued alterations in neuromuscular control[11] it is not clear which SEMG measuring method would inform the RTS decision regarding readiness to return to sport.[10] SEMG can provide information about: the absolute magnitude of muscle activation, the relative timing of muscle activation during a single action, and changes in magnitude and timing during repeated actions.

Regarding the absolute magnitude, ACLR patients likely have a reduction in quadriceps activation. Quadriceps strength is often reported to be lower during MVIC strength testing (compared to their uninjured leg[12] and controls[13]) even years after returning to sport and quadriceps and hamstring strength reductions are associated with reduced performance and risk of reinjury in ACL reconstructed individuals compared to controls at RTS[14,15] and up to four years after surgery.[16] Changes in muscle activation are thought to play a role in these deficits[13] as strength loss does not fully explain the biomechanical differences observed between athletes that did not sustain re-injury after ACLR (greater knee flexion, increased contact time).[17] Persistent neuromuscular alterations which could be related to risk of re-injury are present after ACLR[18] and can be identified during the rehabilitation process.[19]

With regard to the timing of muscle activation, co-contraction of the quadriceps and hamstrings at the time of landing is thought to be a protective mechanism for knee joint stability. Neuromuscular alterations, including earlier thigh muscle onset and increased duration of activation pre-landing, are seen in ACLR athletes during a variety of different drop jump landing tasks[20] and after inducing fatigue.[21] Information regarding time to peak activity are sparse but delayed time to peak activation in quadriceps and hamstrings compared to the healthy leg has been reported in a jump cut task in ACLR males,[22] which may negatively affect attenuation of knee loading during drop jump landing.[23] Athletes who have undergone ACLR have also shown lower quadriceps activation but increased hamstring pre-activity often thought of as protective mechanism to control translation before landing in a repeated jump squat task.[24]

Commonly, ACLR is conducted using either an autologous hamstring (HS) or bone-patellar-tendon-bone graft (BTB). The surgical technique is seen to have an effect on quadriceps and hamstrings muscle strength[15] but it is not known if there are persisting differences in relative activation of these muscles during repeated functional tasks.

A single leg countermovement jump appears to be a valid return to sport test that will identify deficits in knee function in ACLR athletes.[25] Information from a single event such as a drop jump or single cutting movement may not represent the full demands of sporting activity where athletes perform repeated movements, often to the point of muscle failure. More information may be found in a repeated hopping task which might reveal differences in muscle activation patterns as athletes' fatigue. A 30-second maximum effort hopping task has been shown to induce decline in physical performance throughout the task.[26]

Therefore, the purpose of this study was to examine quadriceps and hamstrings muscle activation during repeated hops in healthy pivoting-sport athletes and those who had undergone ACLR (bone-tendon-bone and semitendinosus graft) who had met functional criteria allowing return to training. In particular, the intent was to document the peak muscle activation of the quadriceps and hamstrings during the initial (first 10 seconds) and final (last 10 seconds) of a fatiguing hop task as well as the typical pattern of muscle activation during the individual hops performed during these periods. By examining both legs of the athletes who had undergone ACLR (both hamstring and bone-patellar tendon-bone grafts) and comparing to uninjured healthy controls the authors attempted to better understand any effect on both the timing and magnitude of activity in relation to surgical technique.

The hypothesis was that there would be a change in time to peak and absolute magnitude of activation as participants tire, and that the surgical technique (graft choice) would be associated with specific differences in the activation patterns seen.

METHODS

STUDY PARTICIPANTS

Male participants ("patients") who had undergone an isolated ACLR either with BTB or HS graft and a comparison cohort of active healthy adults ("control") were recruited for the study. All patients participated in pivoting sports and were all at level 9 or 10 on the Tegner scale. The athletes had completed all clinical criteria (<10% deficit on isokinetic and functional field testing, pain-free, no swelling on swipe test, and full ROM)[27] and had demonstrated competence in repeated single leg hops during rehabilitation. All controls were injury-free in the last three months prior to the assessment, had never had a major lower limb injury such as a 3rd degree ligament sprain or ACLR, fracture of bone in lower leg, or 3rd degree muscle strain which could affect neuromuscular profiles. Informed consent was obtained for each volunteer participant and the experiment was conducted with the approval of the local ethics committee.

RECORDING OF MUSCLE ACTIVATION AND NORMALIZATION

Muscle activation was examined[28] by means of wireless surface electromyography (SEMG) signals (hereafter termed 'muscle activation') of the quadriceps muscles (vastus medialis and vastus lateralis) and hamstrings muscles (lateral hamstring and medial hamstring) of both legs during a minimum of 30 seconds repeated single leg countermovement hopping.

SEMG data collection was performed after a 10-minute warm up on a stationary bike, by having skin shaved and cleaned with alcohol swabs (70%), and electrodes were placed following SENIAM guidelines.[28] Muscle activation SEMG from vastus medialis and vastus lateralis and lateral hamstrings and medial hamstrings were recorded at 2000 Hz using a Delsys Trigno Wireless System (Boston, MA), with rectangular electrodes (sized 37mmx26mmx15mm), and a SEMG signal band-with of 20-450Hz. For normalization purposes, each subject's maximal voluntary isometric muscle activation (MVIC) was then assessed with SEMG. Both muscle groups were tested in 60° knee flexion using a hand-held dynamometer, fixated with a belt, for a total of three repetitions of five seconds MVIC for each leg, with one minute's rest in between each repetition. During quadriceps testing the participants were sitting while during hamstrings testing, subjects were lying prone. Standardized instructions and verbal encouragement were provided during testing.

TESTING PROCEDURE

A 3-axis accelerometry inertial measurement unit was placed on the sacrum to identify foot contact and toe-off based on its acceleration signal.[29] The toe-off event was defined as the maximum acceleration value prior to the flight phase and the initial foot contact was defined as the point when the acceleration exceeded 1g after the flight phase on its way to reach maximum value during the load absorption phase. The flight phase was defined where the acceleration was consistently below 1g (Appendix A). The time events from the accelerometer were finally synchronized with the SEMG signal.

Instructions for the jumping task were given immediately before the task was executed, and the participants were asked to perform a minimum of one familiarization trial (without recording) to confirm they understood the task. Participants were instructed to start the test and to hop on one leg as high as possible and as fast as possible until the test was terminated vocally by the examiner who ensured the athletes hopped at least 30 seconds. Athletes who did not hop for 30 seconds were excluded from the data (one participant from BTB group).

DATA PROCESSING AND STATISTICAL ANALYSIS

Data from all the hops for each subject, for each leg, were explored with a customized Matlab script for visualization and analyses of SEMG and accelerometer signal. The accelerometer data were low-pass filtered with a 5 Hz finite-impulse-response (FIR) and the SEMG signal was filtered using 8th-order band-pass filter, with high pass cut at 30Hz and low pass cut at 500Hz using Matlab (R2022a, The Mathworks Inc, Natick, MA). After this, data for each hop was extracted and normalized from one toe off to the following and presented as 101 data points (0-100%) with foot contact centered to 50%. The relative SEMG (%MVC) was then used for subsequent analysis for each of the 101 (0-100%) time points for each hop. Every hop sequence was divided into three phases based on the total hop count for that individual. Where the total number of hops was not exactly divisible by three, care was taken to ensure that the first and third phases had an identical number of hops. Separate analyses were conducted examining: the overall peak activation (magnitude and point of peak); and the relative activation patterns averaged from all hops in each of the three phases during the entire 30-second period.

Peak SEMG activation for each participant was compared between legs using linear mixed models. Distributions (including linear mixed model residuals) were examined using frequency histograms, Q-Q plots, and Shapiro Wilk testing. Descriptive statistics were then calculated, and subsequently linear mixed models for each muscle group were created for their average peak normalized SEMG with fixed (group and leg) and random (participant) effects used to identify main differences and interaction effects. Subsequent pairwise comparisons with Tukey post-hoc corrections were done for each muscle group examining peak SEMG activation across all hop phases for each patient group and leg.

For the control group, no significant differences were found comparing left and right legs so data for a single healthy leg was randomly extracted from both left and right legs for further analyses. For the patient cohort, data are presented for both their operated ("injured") and uninjured legs.

Spatial Parametric Mapping[30] (SPM) was conducted in Matlab (version: 2018a, The Mathworks Inc., Natick, USA)

Table 1. Mean number of jumps ± standard deviation (SD) performed for the different groups and legs during the 30 seconds.

Group	BTB		HS		Controls
Leg	Healthy	Injured	Healthy	Injured	Healthy
Jumps	41.5±7.0	41.8±7.4	44.0±4.7	43.6±6.8	42.4±4.1

to compare the activation pattern of the hop cycles during the first and third hop phases. The significance level was set to p<0.05.

RESULTS

Forty-four male participants were included. Over half of the participants had undergone ACLR with a HS graft (n=24; age 22.2± 4.83 years, weight 74.9±11.87 kg, and height 178.3±9.22 cm) and the rest using BTB reconstruction (n=20; age 22.4±4.89 years, weight 72.0 ±10.58.1 kg, and height: 174.1±7.46. cm), and both groups were on average eight months (±2.8 months) post-surgery. Thirty-one injury-free male footballers (age 24.5 ± 4.23 years, weight 72.7 ± 9.49kg, height 177.1 ± 7.53 cm) were recruited as controls.All included participants were able to perform the minimum 30 seconds' hop testing task on each leg. The number of hops completed in the 30 seconds ranged from 21 to 56 results from groups are present in Table 1.

Figures 1 and 2 show the average activation for the 1st, 2nd, and 3rd phases of the 30 seconds' hop task. SPM analysis comparing the first and third phase of the repeated hop cycle for quadriceps activation revealed statistically significant differences in activation levels (an effective shift to earlier in the hop cycle, Figure 1) of peak vastus medialis and vastus lateralis activation in the control group, in the BTB healthy and injured, and healthy HS group. The SPM for hamstring activation revealed statistically significant differences in activation levels for lateral hamstring in all but BTB-injured group and medial hamstring in the control group only (Figure 2).

Linear mixed model analysis results revealed lower peak activation levels of the vastus lateralis (p=0.001, CI 95%: 27.9 to 41.3) and vastus medialis (p=0.001, 95% CI: 39.0 to 59.6) with a main effect of leg, showing a lower activation in the injured compared to healthy legs. For lateral hamstrings there were significant between group differences (p<0.009) in peak activation with BTB lower than controls (p<0.035, 95% CI: -43.1 to -1.3) and HS lower than controls (p<0.029, 95% CI: -41.4 to -1.8) with main effect seen in healthy legs (lower) compared to injured. Linear mixed model analysis showed a significantly lower peak muscle activation in the medial hamstring with main affect seen between 1st and 3rd phase of the hop cycle in all groups (p=0.022, 95% CI: 0.6 to 10.0).

DISCUSSION

The main findings of the present study show a shift in quadriceps and hamstrings peak activation - an earlier peak activation in the hop cycle in relation to foot contact as the participants repeatedly maximally executed single leg hops for 30 seconds. This pattern for quadriceps and lateral hamstrings muscles was seen in all groups but was not statistically significant for the injured leg of the BTB group. The same pattern was seen for medial hamstrings but the shift in peak activation was only statistically significant in the control group.

The changes in activation pattern during the 30 seconds' maximal hops may have implications for return to sport testing. The timing of peak activation of the quadriceps and hamstrings relative to foot contact likely influences tibial translation. The results demonstrated that quadriceps and hamstrings peak activation generally occurred earlier in the hop cycle, ultimately prior to foot contact, as the repeated hop cycle progresses. The authors suggest that a more complete picture of motor behavior during hopping is provided by this repeated hopping task and venture that this may be more relevant to many sporting contexts where repeated efforts are required. The authors further suggest that clinicians should be cautious in extrapolating from an isolated hop test (as is commonly performed at discharge testing[31]) if the aim is to understand an individual's motor behavior during repeated hopping.

The shift in activation during the repeated hop task was only revealed through analyzing activation during the entire hop task and comparing the activation across the entire 30 seconds' hopping. More commonly, SEMG is analyzed as a single scalar value – e.g., peak activation during the task. Examining the entire movement instead of an arbitrary point in the movement, or a single scalar such as peak activation during the entire action, may therefore allow a better appreciation of the change in motor pattern during the task. This approach may be a useful addition to existing return to sport functional testing which may ultimately shed light on risk of re-injury[32] and other posttraumatic problems (pain, weakness, instability, osteoarthrosis).[4,33,34]

This alteration in motor pattern seen during the 30 seconds' hopping may be in response to fatigue, tibial translation, or other factors.[35,36] Researchers looking at the effect of fatigue on neuromuscular control have shown more co-contraction and higher activation in the leg muscles at contact and in ACLR athletes earlier muscle pre-activation during landing task to establish knee stability.[21] In our study, despite peak activation moving closer to foot contact, repeated hopping was not associated with higher activation of the quadriceps or hamstrings, conversely in our study lower peak quadriceps activation in the ACLR leg was observed in the BTB and HS groups compared to the uninjured leg and compared to the Control group. Previously, de-

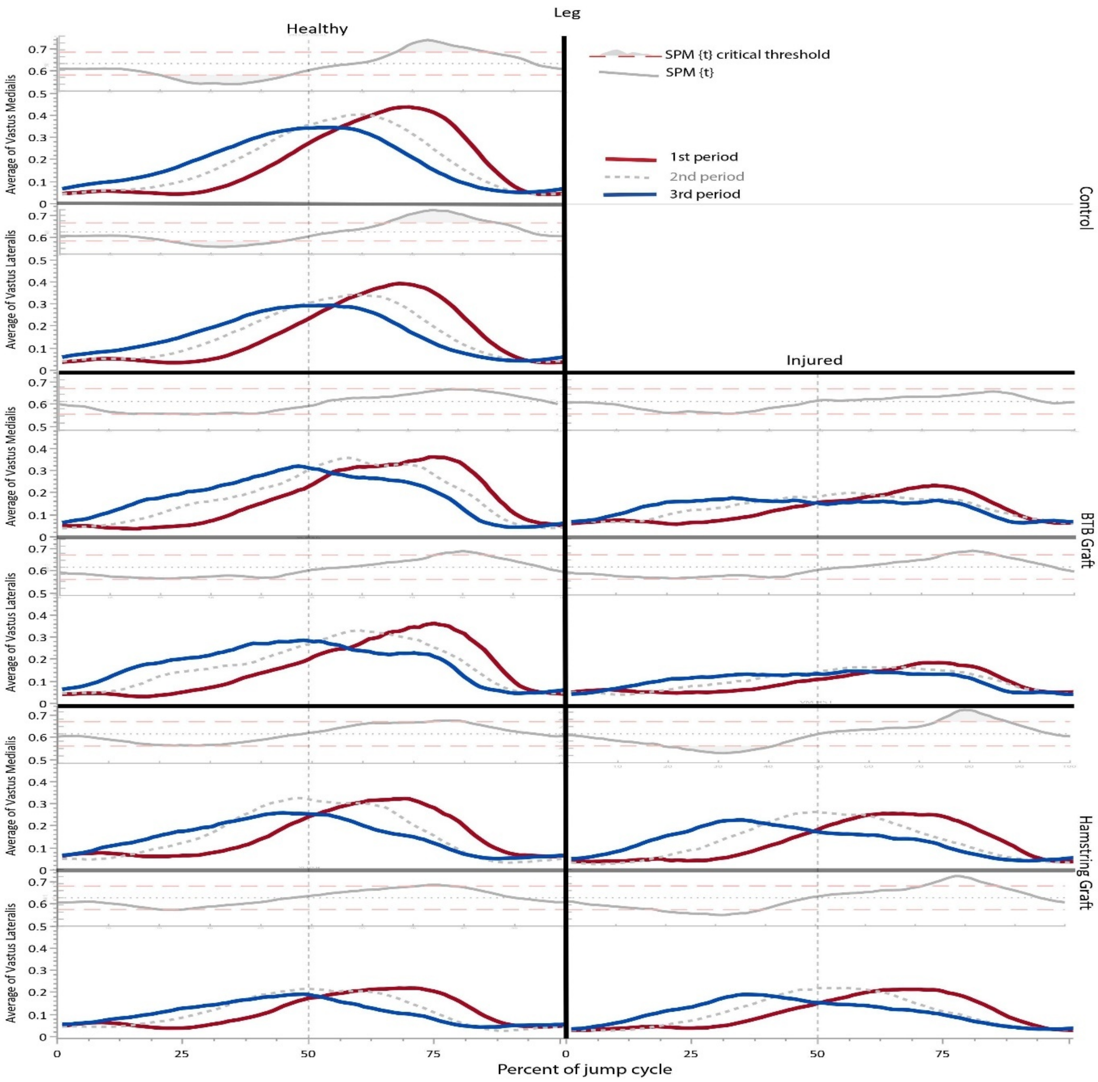

Figure 1. Mean vastus lateralis (VL) and medialis (VM) activation comparison between the first (red) and the last (blue) period during the 30-second vertical hop task.

Each panel illustrates the mean for the first phase (red) second phase (dotted gray) and the last phase (blue) of the hop task. The Y-axis represents the relative muscle activation compared to maximum voluntary contraction (0-1, vertical scale truncated to 0-0.7 for clarity) and the X-axis represents the entire hop phase with foot contact at 50% (0-100) presented with dotted vertical line. Within each panel, the inset above illustrates the Statistical Parametric Mapping comparing the first and third hop periods. The thick black line depicts the test statistic continuum, which in this case is a *t* continuum, or "SPM{t}" The red hashed line depicts the critical threshold at *alpha* = 5%. From a classical hypothesis testing perspective, the null hypothesis is rejected at *alpha* if the SPM{t} exceeds this threshold, indicated by the shaded grey area where p<0.05. No statistical analyses were made using the 2nd period; it is shown for reference only.

creased quadriceps and hamstrings activation has been reported in ACLR athletes after a sequence of fatiguing deep squats followed by a dynamic jump endurance protocol[37] suggesting fatigue may be an influencing factor for this observation.

Overall, few differences in activation patterns were observed between the HS and BTB groups. In contrast, previous researchers examining a dynamic forward hop task reported increased quadriceps before landing ("pre-activation") for the HS ACLR participants, while the BTB- graft group did not present a clear pre-activation pattern.[38] The different tasks – vertical compared to horizontal hops – likely contribute to the different results.[25,39] In healthy knees[35] and in the ACLR knees,[40] tibial anterior translation increases with quadriceps pre-activation[40] and adequate hamstring activation can be important to control the translation[36] while low quadriceps amplitude decreases the attenuation of landing forces.[23] Fatigue is known to affect the magnitude of hamstrings activation[41] which agrees with the findings of present study as the authors found a decline in medial hamstring activation from the 1st to 3rd phase of the hop cycle was present in all groups The shift in activation to earlier in the hop cycle could represent a protective strategy to minimize tibial translation through co-contraction prior to foot strike.[42,43]

The athletes examined in the current study had demonstrated >90% between-leg symmetry in isokinetic tests of knee flexion and extension strength. During the repeated

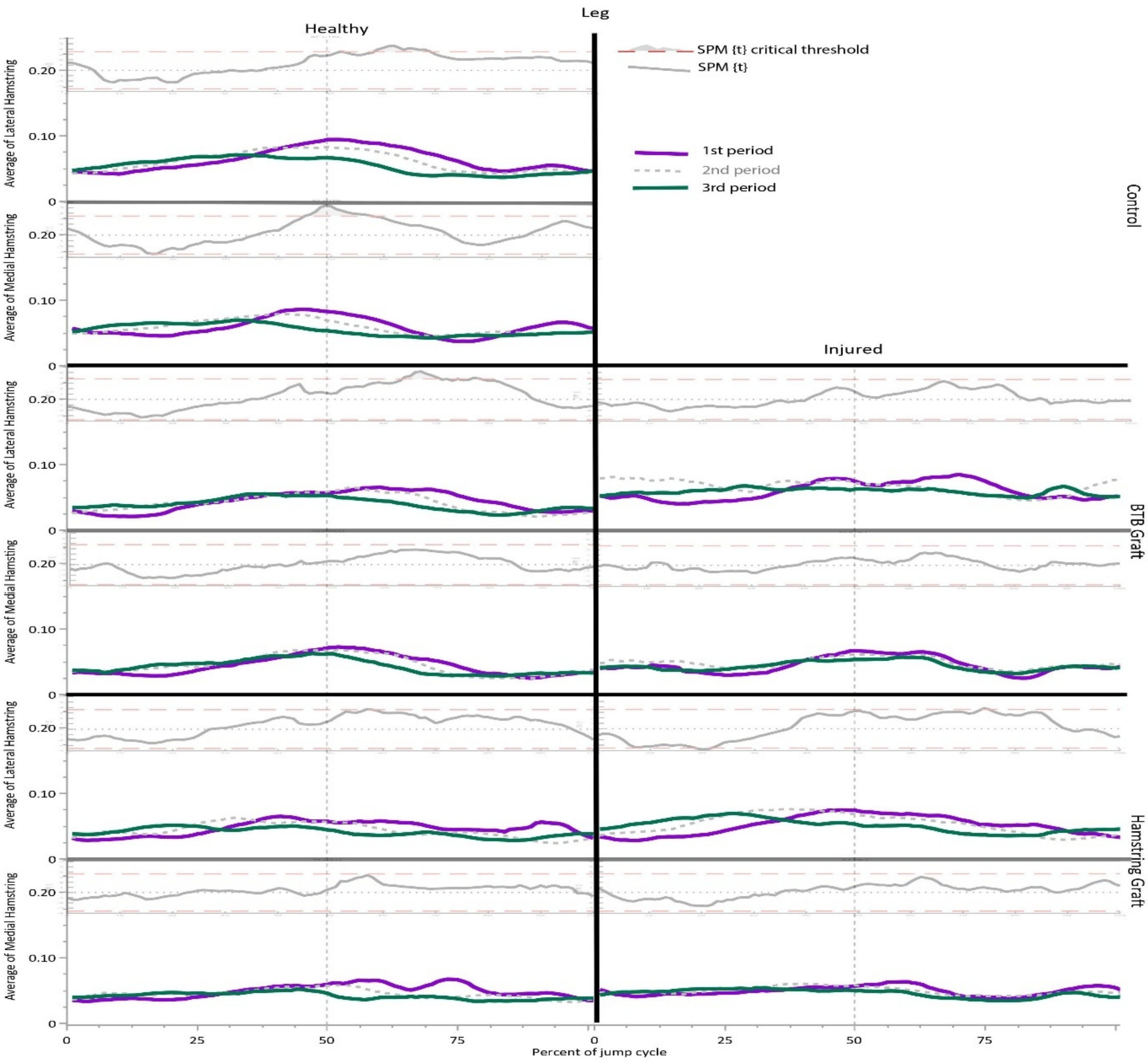

Figure 2. Mean lateral and medial hamstring activation comparison between the first (purple) and the last (green) period during the 30-second vertical hop task.

Each panel illustrates the mean for the first phase (purple) second phase (dotted gray) and the last phase (green) of the hop task. The Y-axis represents the relative muscle activation to maximum voluntary contraction (0-1, vertical scale truncated to 0-0.2 for clarity) and the X-axis represents the entire hop phase with foot contact at 50% (0-100) presented with dotted vertical line. Within each panel, the inset above illustrates the Statistical Parametric Mapping comparing the first and third hop periods. The thick black line depicts the test statistic continuum, which in this case is a *t* continuum, or "SPM{t}" The red hashed line depicts the critical threshold at *alpha* = 5%. From a classical hypothesis testing perspective, the null hypothesis is rejected at *alpha* if the SPM{t} exceeds this threshold, indicated by the shaded grey area where p<0.05. No statistical analyses were made using the 2nd period; it is shown for reference only.

hopping task, reduced peak activation of the quadriceps and hamstrings was observed for the ACLR leg. Previous research examining vertical and horizontal hop tasks suggests ACLR patients adopt a strategy shifting work away from their knee to their hip and ankle.[25,39] While not investigated in the present study, this would plausibly explain these findings (of reduced peak activation) despite apparent adequate knee strength. Differences in muscle activation are commonly presented in ACLR male athletes during jump testing but results are mixed showing decreased,[24] or increased activation.[44,45] The disparities in results could be related to differences in testing i.e., cohort, protocol, and normalization methods.[46]

LIMITATIONS

While this research has shown alterations in activation patterns, the current research did not consider any kinematic or kinetic implications of these which now should be addressed in future research given these findings. Due to the lack of kinematic data we are unable to determine whether the changes seen in muscle activation are related to changes in kinematic or kinetics[47] and/or reduced jump height.

The patients examined in this study had reached clinical discharge criteria,[27] but the time taken to do so varied (5 to 12 months). The present study is not powered to examine the effect of time since surgery, and it is possible that the athletes continue to alter their neuromuscular profiles across their rehab and beyond, nevertheless differences in muscle activation have been reported 1-2 years post ACLR in functional movements.[23,25]

The current research included only hamstring and patellar tendon grafts, other graft choices (e.g. quadriceps tendon, allografts, artificial ligaments, etc) would likely yield different results again. It should also be noted that the control group consisted only of professional footballers while the ACLR group included professional athletes playing football, futsal, rugby, handball, and volleyball.

CONCLUSION

A shift in activation of the thigh muscles was shown (earlier) as the 30-second hop task progressed. EMG analysis of single hops is therefore not necessarily representative of the muscles' activation patterns and the changes seen during repeated hops. Repeated jump and hop testing protocols that induce endurance and motor control challenges probably provide complementary information to return to sport testing which may be more relevant to many sports where repeated efforts are required.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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SUPPLEMENTARY MATERIALS

Appendix A

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