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OPEN

Electromyography Evaluation of Bodyweight Exercise Progression in a Validated Anterior Cruciate Ligament Injury Rehabilitation Program

A Cross-Sectional Study

Mette Kreutzfeldt Zebis, PhD, Mads Hjorth Sørensen, PT, Hanne Bloch Lauridsen, MSc, Jesper Bencke, PhD, Christoffer Højnicke Andersen, PhD, Jacob B. Carlsbæk, PT, Patrick Jespersen, PT, Anders H. Kallehauge, PT, and Lars Louis Andersen, PhD

Objectives: Regaining muscle strength is essential for successful outcome after anterior cruciate ligament injury, why progression of exercise intensity in anterior cruciate ligament injury rehabilitation is important. Thus, this study evaluated hamstring and quadriceps muscle activity progression during bodyweight exercises used in a validated anterior cruciate ligament injury rehabilitation program.

Design: The study design involved single-occasion repeated measures in a randomized manner. Twenty healthy athletes (nine females) performed nine bodyweight exercises (three exercises per rehabilitation phase). Surface electromyography signals were recorded for hamstring (semitendinosus, biceps femoris) and quadriceps (vastus medialis, vastus lateralis) muscles and normalized to isometric peak electromyography.

Results: Hamstring muscle activity did not increase from one rehabilitation phase to the next, ranging between 8% and 45% normalized electromyography for semitendinosus and 11% and 54% normalized electromyography for biceps femoris. Only one exercise (Cook hip lift) exhibited hamstring muscle activities more than 60% normalized electromyography. By contrast, quadriceps muscle activity increased, and late-phase exercises displayed high normalized electromyography (vastus lateralis >60% and vastus medialis >90% normalized electromyography).

Conclusions: The examined bodyweight exercises did not progress for hamstring muscle activity but successfully progressed for quadriceps muscles activity. This study highlights the need for consensus on exercise selection when targeting the hamstring muscles in the rehabilitation after anterior cruciate ligament injury.

Key Words: Knee, Neuromuscular Activity, Lower Extremity, Training

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Anterior cruciate ligament (ACL) injury is one of the most serious sports-related injuries, causing both instant and long-term consequences, such as pain, disability, and ultimately joint degeneration.[1] In physical therapy, evidence-based and well-designed rehabilitation programs play a key role in any successful outcome after ACL injury. Successful outcomes include a return to unrestricted activities and preinjury levels.[2,3] However, there is only limited consensus regarding which exercises to include in the rehabilitation after ACL injury.[4,5] Thus, researchers and practicians recommend a wide range of rehabilitation protocols[6–8] with common focus on knee range of motion, isometric quadriceps activation, and early weight bearing exercises in the initial phase of rehabilitation.[6–8] In the mid-phase of rehabilitation, focus is on recovering full knee range of motion, removing all swelling, incorporating strength training for relevant muscles, and regaining normal walking and stair function. In the final phase, also called the return to sport phase, it is generally agreed that plyometric, one-legged exercises and sport-specific exercises are relevant.[6–9] Thus, the intensity (ie, level of muscle activity) of exercises is intended to progress from one rehabilitation phase to the next.

One main focus in the rehabilitation after ACL injury is to introduce safe exercises that target the quadriceps muscles at appropriate activity levels in a progressive manner.[4] However, reduced lower limb muscle strength is reported not only in the quadriceps but also in the hamstring muscles after ACL injury and reconstruction, often lasting well beyond the postoperative rehabilitation period.[10,11] During forceful dynamic movements, co-activation of the hamstrings is important to provide dynamic knee joint stabilization and to prevent excessive

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ACL shear forces.[12,13] Consequently, the hamstring muscles are considered important ACL agonists, and especially the ability to adequately activate the medial hamstring muscle (semitendinosus) plays a key role in the protection of the ACL.[14] Thus, exercises that target the hamstring muscles at appropriate activity levels and in a progressive manner should have high priority in ACL injury rehabilitation.

A fundamental element in muscle strength progression is the intensity of exercise, which can be defined as a given percentage of the maximal muscle contraction strength.[15] Surface electromyography (EMG) is often used as an indicator of intensity of exercise because a positive linear relationship between isometric muscle force and surface EMG amplitude has been documented previously.[16–18] Moreover, a positive proportionate relationship exists between muscle force and EMG amplitude during dynamic muscle contraction, although this relationship may be slightly curvilinear in some muscles.[19–21] Normalization of the EMG amplitude with respect to the maximal EMG amplitude obtained during isometric conditions increases the reliability of the measurements.[22–26] Thus, normalized EMG (nEMG) amplitude expressed as a percentage of the maximal EMG amplitude provides an approximate estimate of exercise intensity and is commonly used in exercise evaluation studies.[27–30]

It is generally agreed that strength training exercises using loading intensities of at least 60% are effective for muscular adaptations to occur, with higher intensities yielding proportionally greater adaptations.[31] To yield high levels of muscle activity, resistance training using specialized training machines or free weights is effective.[27] However, in clinical practice and for home-based rehabilitation, conventional resistance training devices are often not available. Thus, the muscle activity of bodyweight exercises used in ACL rehabilitation is highly relevant to investigate. Furthermore, resistance training can easily be progressed by increasing external load, but whether bodyweight exercises progress between ACL rehabilitation phases remain to be evaluated. Thus, the aim of this cross-sectional study was to evaluate the progression of bodyweight exercises used in a previously validated ACL injury rehabilitation protocol[9] in healthy athletes. The primary outcome was normalized muscle activity of the hamstring muscles measured by use of EMG. Secondary outcome was quadriceps normalized muscle activity. We hypothesized that (*a*) hamstring muscle activity and (*b*) quadriceps muscle activity would progress (ie, increase) from one rehabilitation phase to the next.

METHODS

Study Design and Participants

The study was performed as a cross-sectional trial with randomized exercise order in Copenhagen, Denmark, in October and November 2017. This study conforms to all STROBE guidelines and reports the required information accordingly (see Supplemental Checklist, Supplemental Digital Content 1, http://links.lww.com/PHM/A804). Study participants were healthy athletes recruited from local sports associations in Copenhagen, Denmark. To resemble the age-group and activity level of the population investigated by Frobell et al.,[9] the inclusion criteria were between 18 and 35 yrs of age and a score of 5 to 9 on the Tegner Activity Scale.[32] Exclusion criteria were previous knee injury, pregnancy, a history of deep vein thrombosis or a disorder of the coagulative system, general systemic disease affecting physical function, and systemic medication/abuse of steroids. In total, 20 participants (9 females) volunteered to participate in the study (mean ± SD: age = 25.2 ± 2.9 yrs; height = 177 ± 10 cm; weight = 75.4 ± 14.3 kg). The subjects participated in a range of sports (including handball, football, fitness, floorball, CrossFit, running, cycling, and American football) and had a training frequency of 4 ± 2 sessions/week. Subjects had on average participated in their respective sports for 16 ± 7 yrs.

All participants were informed about the purpose and content of the project and provided their written informed consent to participate in the study in accordance with the Declaration of Helsinki. According to the Act on Research Ethics Review of Health Research Projects, the Committees on Biomedical Research Ethics for the Capital Region of Denmark did not consider the study as a health research study, and thus, the study did not need to be notified for full ethical evaluation by the committee (Journal Number 17028314).

Test Day Procedure

The participants were tested in a clinical motion analysis laboratory on one single occasion. On the test day, the participant was introduced to the laboratory and the test protocol. The test protocol consisted of the following five procedures (in chronological order): (*a*) measurement of anthropometric data (age, height, weight, and determining dominant leg), (*b*) positioning of bipolar EMG electrodes, (*c*) standardized warm-up procedure, (*d*) test of maximum voluntary isometric contraction (MVIC), and (*e*) rehabilitation exercises in a randomized manner.

Anterior Cruciate Ligament Rehabilitation Protocol

The ACL rehabilitation protocol chosen in this study[9] refers to a systematic review extracting evidence from 33 randomized controlled trial studies.[4] The rehabilitation protocol consists of five phases covering a rehabilitation period of 24 wks.[9] Each phase has the following five overall goals: range of motion, muscle function, symptoms, walking function, and balance/coordination. To progress from one phase to the next, all goals have to be achieved by the ACL patient. Examples of exercises, which are included in the rehabilitation protocol, are presented in an appendix[33] representing four of five rehabilitation phases.[9] Twenty-four exercises are illustrated with a short explanatory text. It is emphasized that the exercises are exemplary and that the physical therapist also used complimentary exercises that followed the guidelines for each phase.

Selection of Exercises

The present exercise evaluation only includes bodyweight exercises. These are defined as exercises that do not require free weights or machines because the individual's own weight provides resistance against gravity.[34]

TABLE 1. Overview of rehabilitation phases and exercises evaluated in the present study

Frobell et al.[9] (2010)	Phase 1 (0–4 wks)	Phase 2 (5–8 wks)	Phase 3 (9–12 wks)	Phase 4 (13–16 wks)	Phase 4–5 (17–24 wks)
Our study	Phase 1 (0–2 wks)	Phase 2 (2–8 wks)		Phase 3 (13–24 wks)	
Hamstring exercise	Prone leg curl	Cook hip lift		Lunges with rotation	
Quadriceps exercise	Supine knee extension with ball	Standing knee extension with ball		Bulgarian split squat	
Squat exercise	Box squat	Bodyweight squat		Forward jump with ball	

In the appendix, "phase 1 and 2" and "phase 4 and 5" are merged, respectively, and "phase 3" is not represented.[33] Based on the structure of the appendix, we choose to evaluate the rehabilitation protocol as three phases (Table 1) to enable a comparison of initial versus late rehabilitation.

Three physical therapist students independently selected three exercises from 0 to 2 wks (phase 1), from 2 to 8 wks (phase 2), and from 13 to 24 wks (phase 3). The criteria for selection was to identify one quadriceps muscle dominant, one hamstring muscle dominant, and one squat-like exercise from each phase. Thus, each physical therapist student individually selected nine exercises (3 × 3), followed by a consensus meeting where disagreements between the physical therapist students were discussed. The nine exercises included in the present study are presented in Figures 1A–C. All exercises were evaluated using EMG.

The exercises were instructed and supervised on-site by a physical therapist student. Only trials that were performed with proper technique were used in the analysis. Three approved trials for each exercise were collected for muscle EMG activity and an average of the three trials, respectively, was used for data analysis.

Outcome Variables

The primary outcome variable was normalized (to isometric MVIC peak amplitude) hamstring muscle EMG amplitude (semitendinosus and biceps femoris) recorded during the nine

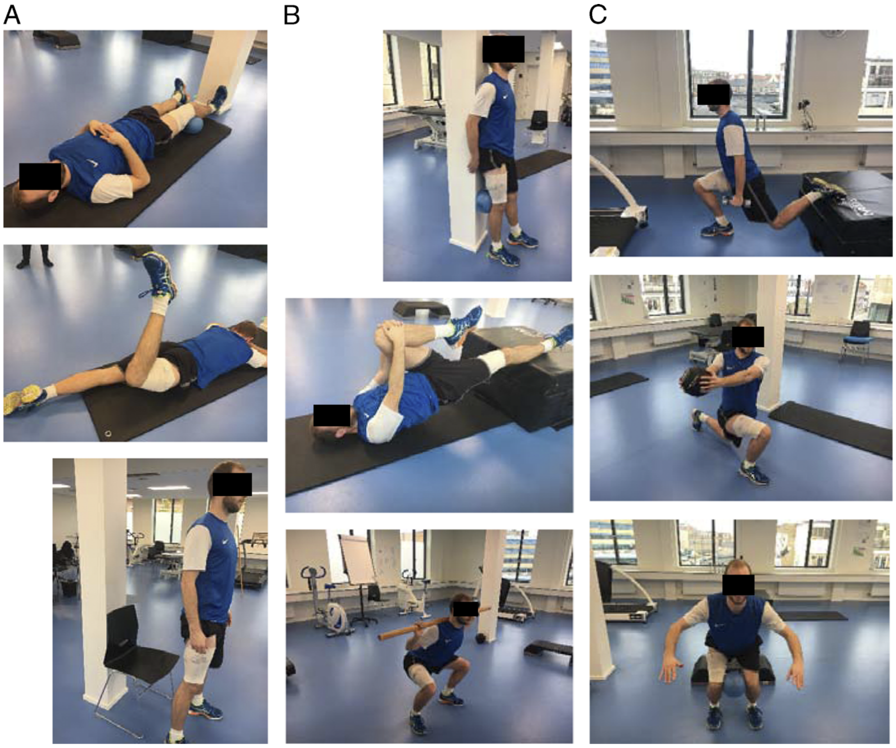

FIGURE 1. Bodyweight exercises. Illustrations of the selected exercises in the respective phases. A, Phase I (0–2 wks). Exercise 1 – *Supine knee extension* with ball: Lay down/sit in front of a wall with your injured leg slightly bent and a ball under the knee. Put the foot against the wall and press the knee toward the floor. Keep tension in the knee extensors. Exercise 2 – *Prone leg curl*: Lay on your stomach, bend the injured knee to approximately 90 degrees, and lift your foot and lower leg toward the ceiling. Exercise 3 – *Box squat*: Sit on a chair/stool. Stand up slowly with full muscle control, equally distributed load on both feet. B, Phase II (2–8 wks). Exercise 4 – *Standing knee extension* with ball: Stand with your back against the wall and a soft ball behind your injured knee. Squeeze the ball against the wall by extending your knee. Exercise 5 – *Cook hip lift*: Lay on your back with the injured leg on a hard pillow, keep your hands around your other knee. Lift your pelvis. Exercise 6 – *Bodyweight squat*: Sit down while keeping the chest up and the entire foot on the floor. Important! Neutral alignment of foot, knee, and hip. Keep chest up. C, Phase III (13–24 wks). Exercise 7 – *Bulgarian split squat*: Stand on one leg with your other lower leg resting on a chair/box. Lower the rear knee toward the floor and push back up with front foot. Important! Neutral alignment of foot, knee, and hip. Use dumbbells for additional loading. Exercise 8 – *Lunges with rotation*: Forward lunges while moving medicine ball outside lead leg. Exercise 9 – *Forward jump* with ball: Squeeze a soft ball between your knees. Jump forward on both legs over a series of step boards. Land "soft."

exercises. Secondary outcome variable was EMG amplitude of the quadriceps muscle (vastus lateralis and vastus medialis normalized to isometric MVIC peak amplitude).

Randomization and Observer Blinding

An envelope was prepared in advance with the randomized order of all nine exercises. The randomization protocol was carried out by use of http://www.random.org. The present study design did not allow for blinding of participants or test leader. However, the researcher performing the statistical analyses was blinded to the exercises.

Electromyography Analysis

EMG signals from four muscles (m. semitendinosus: ST, m. biceps femoris: BF, m. vastus medialis: VM, m. vastus lateralis: VL) in the preferred push-off leg were analog/digital sampled (1000 Hz) using wireless bipolar electrodes (Noraxon USA, Inc). Before electrode placement, the skin of the subject was shaved with a hand razor and carefully cleaned with ethanol. Bipolar surface EMG electrodes (Neuroline 720 01-K; Medicotest A/S, Olstykke, Denmark) were placed according to standardized procedures.[35]

All raw EMG signals were prepared for later off-line analysis by a fourth-order high-pass filtering with a cutoff frequency of 10 Hz and subsequent low-pass filtering using a moving (1-millisec steps) root-mean-square filter with a 30-millisec time constant, using custom-made algorithms written in Matlab (MathWorks Inc, Natick, MA). After a standardized warm-up program, three trials of MVIC for the hamstring and quadriceps muscles, respectively, were performed (detailed description hereinafter). The peak EMG amplitude obtained during MVIC from each muscle (identically filtered) was used for normalization of the peak EMG values obtained during the respective exercises—termed nEMG (ie, normalized EMG).

Maximum Voluntary Isometric Contraction

Before measuring the MVIC all participants went through a standardized warm-up procedure consisting of ten countermovement jumps (individualized to correspond to 50% of max effort), ten one-leg squats on each leg, ten countermovement jumps (80% of max effort), ten lunges on each leg, and finally ten maximal countermovement jumps (100% effort).

Knee extensor MVIC EMG activity was obtained with the participant lying supine on an examination bed with a foam roller (diameter 15 cm) placed below the knee to ensure a slight knee flexion. The pelvis was fixated to the examination bed by a nonelastic strap. The handheld dynamometer (Hoggan, MicroFET2) was placed on top of the lower leg in a distance corresponding to the width of two fingers above the medial malleolus. A nonelastic strap was attached from the handheld dynamometer to the examination bed to ensure that no knee movements would occur during testing. Excellent intraclass correlation coefficient (0.929, 95% confidence interval [CI] = 0.857–0.966) has been reported with this procedure.[36] Knee flexor MVIC EMG activity was obtained with the participant positioned prone on the examination bench at 10-degree knee flexion, the ankle free of the bench's edge, a strap (attached to the floor) wrapped around the ankle and then performing a maximal isometric knee flexor contraction.[37] All MVIC lasted 4 secs to allow for maximal muscle activity and strong verbal encouragement was given to the subjects. Three MVIC trials were performed for each muscle with a 30-sec rest between each trial to avoid fatigue accumulation.

Perceived Loading

Immediately after each set of exercise, the Borg CR10 Scale[38] was used to rate perceived loading after each exercise. The meaning of the scale was carefully explained to each individual before testing.

Sample Size Calculation

A priori power analysis showed that 16 subjects in this paired design were sufficient to obtain a statistical power of 80% at a minimal relevant difference between exercises of 10% with an α level of 5%.[39]

Statistical Analysis

A general linear model (Proc GLM, SAS Version 9.4; SAS Institute, Cary, NC) was used to determine differences between muscles and exercises in nEMG. *Muscle* (BF, ST, VM, VL), *exercise* (9 exercises) and *muscle by exercise* interaction were fixed factors. Normalized EMG was the dependent variable. Subject was entered in the model as a random factor. Values are reported as least square means (95% CI), unless otherwise stated. *P* values of less than 0.05 were considered statistically significant. Statistically significant difference exists if the CI for one exercise/phase/muscle does not overlap the mean value of the exercise/phase/muscle being compared with.

Perceived exertion is presented as descriptive data.

Definition of Muscle Activity Progression

Progression from one phase to the next was defined as a significantly higher level of muscle activity for a given muscle (eg, in BF) in an exercise (eg, hamstring dominant) related to the next phase (eg, phase 1 < phase 2).

Definition of Medial vs Lateral Dominance

Based on the statistical analysis, an exercise was defined as a lateral dominant exercise if the lateral muscle exhibited significantly higher muscle activity compared with the medial muscle of the same muscle group (ie, VL > VM, BF > ST) and vice versa for a medial dominant exercise.

Definition of Hamstring vs Quadriceps Dominance

Based on the statistical analysis, an exercise was defined as a hamstring muscle dominant exercise when the muscle activity of both hamstring muscles were significantly higher than the muscle activity of both muscles of the quadriceps (ie, ST muscle activity > VM and VL muscle activity *and* BF muscle activity > VM and VL muscle activity) and vice versa for a defined quadriceps muscle dominant exercise.

RESULTS

Progression of Hamstring Muscle Activity

The levels of BF muscle activity progressed—in ascending order—(*box squat*, *standing knee extension*, *bodyweight* *squat*) < (*Bulgarian split squat*, *lunges with rotation*) < (*supine knee extension*, *forward jump with ball*) ≤ (*Cook hip lift*) ($P < 0.05$). For the BF, high level of muscle activity (ie, >60% nEMG) was observed in *Cook hip lift*, phase 2 (64% nEMG [95% CI = 53%–75%]).

For the ST, high level of muscle activity (ie, >60% nEMG) was observed in *Cook hip lift*, phase 2 (64% nEMG, 95% CI = 53%–74%). The levels of ST muscle activity progressed—in ascending order—(*supine knee extension, box squat, standing knee extension, bodyweight squat*) < (*prone leg curl*, *Bulgarian split squat*, *lunges with rotation*, *forward jump with ball*) < (*Cook hip lift*).

Progression of Quadriceps Muscle Activity

For the VL, high levels of muscle activity (ie, >60% nEMG) were observed in phase 3 during *Bulgarian split squat*, *lunges with rotation*, and *forward jump with ball*. Levels of VL muscle activity progressed significantly—in ascending order—(*prone leg curl, Cook hip lift*) < (*supine knee extension, box squat*) < (*standing knee extension, bodyweight squat*) < (*Bulgarian split squat, lunges with rotation, forward jump with ball*).

For the VM, high levels of muscle activity (ie, >60% nEMG) were observed during *bodyweight squat, Bulgarian split squat, lunges with rotation*, *and forward jump with ball*. The levels of VM muscle activity progressed significantly—in ascending order—(*prone leg curl, Cook hip lift*) < (*supine knee extension*) < (*box squat, standing knee extension*) < (*bodyweight squat*) < (*Bulgarian split squat, lunges with rotation, forward jump with ball*).

Hamstring vs Quadriceps Activation Balance

Prone leg curl and *Cook hip lift* were hamstring muscle dominant exercises (Table 2). In *supine knee extension* (phase 1), a preferential activation of the BF (54% nEMG [95% CI = 43–65]) was observed over ST (18% nEMG [95% CI = 7–29]) and quadriceps (VL: 32% nEMG [95% CI = 21–43] and VM 30% nEMG [95% CI = 19–41], $P < 0.05$). *Box squat, standing knee extension, bodyweight squat, Bulgarian split squat, lunges with rotation, and forward jump with ball* were quadriceps muscle dominant exercises (Table 2).

Lateral-Medial Activation Balance

Except for *supine knee extension*, no significant differences were found between BF and ST nEMG amplitude in any of the remaining exercises (Table 2). Of the six quadriceps dominant exercises, five exercises displayed a preferential activation of the VM over VL. In phase 3, all three exercises were VM dominant exercises ($P < 0.05$).

Perceived Exertion

In the three phases, respectively, the precategorized hamstring exercise was rated highest. Perceived exertion after execution of the nine exercises, respectively, was between 0.8 and 3.2 (Table 2). The highest perceived exertion was registered in phase 3 during *lunges with rotation* where muscle activity between 32% and 96% nEMG were observed. The lowest rated exercise (*box squat*) elicited muscle activity levels between 11% and 60% nEMG in the respective examined muscles.

DISCUSSION

The main finding of the present EMG evaluation was that the examined bodyweight exercises primarily targeted the quadriceps muscles and especially the medial quadriceps muscle (vastus medialis). Furthermore, the present study found that only one of the examined bodyweight exercises elicited hamstring muscle activity levels more than 60% nEMG. The exercises did not progress as hypothesized for the hamstring muscles, and phase 1 (0–2 wks) and 3 (13–24 wks) displayed the same low to moderate levels of hamstring muscle activity. In phase 3, muscle activity levels for the hamstring muscles were between 26% and 45% nEMG indicating that the bodyweight exercises in the present rehabilitation protocol were unlikely to stimulate strength gains in the knee flexors.[40] In contrast, quadriceps muscle activity increased significantly from one phase to the next corresponding to a progression through phases. The final rehabilitation phase (phase 3) included exercises that elicited high quadriceps muscle activity levels (ie, >60% nEMG). Overall, seven of the nine examined bodyweight exercises were quadriceps dominant exercises, which—in combination with the observed low levels of hamstring muscle activity—highlights the need for consensus on exercise selection and exact dose response when targeting the hamstring muscles in the rehabilitation after ACL injury.

TABLE 2. Normalized EMG (95% CI) for each muscle during the nine exercises in the respective phases

Phase	Exercise	BF nEMG	ST nEMG	VL nEMG	VM nEMG	Borg CR10
Phase 1	Supine knee extension (Qua dominant)	54 (43–65)	18 (7–29)	32 (21–43)	30 (19–41)	1,2
	Prone leg curl (Ham dominant)	31 (20–42)	40 (29–51)	18 (7–29)	10 (0–21)	1,9
	Box squat (Squat dominant)	11 (0–22)	17 (6–28)	36 (25–47)	60 (49–71)	0,8
Phase 2	Standing knee extension (Qua dominant)	11 (0–22)	8 (0–19)	52 (41–63)	54 (44–65)	1,3
	Cook hip lift (Ham dominant)	64 (53–75)	64 (53–74)	11 (0–22)	10 (0–20)	2,6
	Bodyweight squat (Squat dominant)	10 (0–21)	12 (1–23)	51 (40–62)	75 (64–86)	2,1
Phase 3	Bulgarian split squat (Qua dominant)	26 (16–37)	31 (20–42)	64 (53–75)	97 (86–109)	3,0
	Lunges with rotation (Ham dominant)	32 (21–43)	37 (26–48)	69 (58–81)	96 (85–107)	3,2
	Forward jump with ball (Squat dominant)	45 (34–56)	45 (34–55)	69 (58–80)	100 (88–111)	1,6

EMG, electromyography; BF, biceps femoris; ST, semitendinosus; VL, vastus lateralis; VM, vastus medialis; Qua, quadriceps; Ham, hamstring; nEMG, normalized EMG.

Hamstring Muscle Group

Two of the three bodyweight exercises precategorized as hamstring muscle dominant (ie, prone leg curl and Cook hip lift) were found to display significantly higher hamstring muscle activity than quadriceps muscle activity. The third exercise, lunges with rotation, was precategorized as a hamstring dominant exercise based on the hip extension during execution. However, this exercise displayed significantly higher quadriceps muscle activity. This finding is supported by Begalle et al.[41] (2012), who found that lunges have a primary quadriceps activation, with a simultaneous hamstring activation.

It is noteworthy that the supine knee extension—being defined as quadriceps dominant exercise—elicited fairly high levels of BF muscle activity. The reason for this is likely that the subjects are instructed to put the foot against the wall and press the knee toward the floor. The last part, pressing the knee toward the floor, involves a hip extension. Because the BF also acts as hip extensor, the finding is not surprising. However, defining this exercise as quadriceps dominant is not correct according to the measurements.

Phase 3 was hypothesized to elicited the highest nEMG values because of the goals of this late phase of rehabilitation (eg, Limb Symmetry Index >90%).[42] However, the bodyweight exercises evaluated in the present study elicited only low to moderate nEMG activity levels for the hamstring muscles. To stimulate the hamstring muscles optimally, especially in the later phases of rehabilitation, it may be relevant to include additional hamstring-specific exercises validated in the scientific literature. Although it can be challenging to find bodyweight exercises that involves high hamstring activation, exercises such as straight knee bridge,[43] supine leg curl,[28] and Nordic hamstring[28] show that there are options available. Eitzen et al.[42] evaluated a 5-wk progressive exercise program in the early phase of ACL injury rehabilitation.[42] This program significantly increased hamstring muscle peak torque by 10% in the injured leg. The program included several high-intensity bodyweight exercises (eg, *hamstring on Fitball*), which elicits high muscle activity levels for both the lateral and medial hamstring muscles.[44] Thus, it seems feasible to include high-intensity bodyweight exercises for the hamstring muscles also in the early/mid phase of rehabilitation of ACL patients.

It is important to emphasize that the present EMG evaluation only included bodyweight exercises why the findings do not represent the stimuli and progression of the overall rehabilitation protocol. Because strength per se was not an outcome measure in the study by Frobell et al.,[9] we are not able to comment on the effectiveness of the protocol on this parameter.

Quadriceps Muscle Group

In 2004, Risberg et al.[4] provided an evidence-based review of the effectiveness of various rehabilitation programs that have been used for surgically or nonsurgically treated ACL injuries in adult patients. In this review, it was emphasized that although all lower extremity muscles must be included in rehabilitation after ACL injury or reconstruction, particular attention must be paid to strengthening the quadriceps, because it is the most affected muscle in these situations.[4] In our study, a significant increase in quadriceps muscle activity from one phase to the next was observed, which implies that bodyweight exercises were successfully progressed in the present rehabilitation protocol. Furthermore, in phase 3 both VL and VM reached activity levels high enough to stimulate strength gains (ie, >60% nEMG).[40] This indicates that the key goal of the late rehabilitation phase (ie, to achieve substantial strength gains) is achievable with the present bodyweight exercises. Furthermore, there is consensus that VMO activation and active knee extension is essential in ACL rehabilitation.[7] In respect to this, all exercises in phase 3 induced quadriceps activity levels more than 60% nEMG with significant VM dominance (ie, 27–34 percentage point higher activity than VL).

Limitations

This study has several limitations. The present study evaluated the exercises in healthy athletes, why we cannot conclude that the findings can be generalized to ACL patients. However, the present EMG evaluation could be considered a healthy reference material for comparison, both of the ACL-injured leg and the healthy leg. Furthermore, the EMG evaluation was only based on bodyweight exercises and examples given in the appendix of the randomized controlled trial study.[9] We acknowledge that other exercises might have displayed a different progression of the present protocol. The present study did not include a familiarization visit; however, the participants were all skilled athletes (ie, the exercises were simple to perform) and only trials performed with proper technique were used in the analysis. Finally, the examined rehabilitation protocol includes five rehabilitation phases. However, based on the structure of the appendix, we choose to evaluate the rehabilitation protocol as three phases to enable a comparison of initial vs late rehabilitation. Measuring all five phases in one setting may increase the risk of fatigue and thus invalid EMG values. Randomizing the exercise order is a strength as the influence of fatigue or any other systematic change is less likely to influence the findings.

CONCLUSIONS

The present evaluation—based on "best practice" examples—revealed that a therapeutic challenge exists in identifying bodyweight exercises that target the hamstring muscles at high activity levels and in a progressive manner. In contrast, quadriceps muscle activity successfully increased in a progressive manner from on phase to the next. This study highlights the need for consensus on exercise selection and exact dose response when targeting the hamstring muscles in the rehabilitation after ACL injury.

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