Physical Therapy in Sport 39 (2019) 69–75

Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

Original Research

Foot rotation influences the activity of medial and lateral hamstrings during conventional rehabilitation exercises in patients following anterior cruciate ligament reconstruction

André Beuchat [a,*], Nicola A. Maffiuletti [b]

[a] Sport Physical Therapy, Schulthess Clinic, Zurich, Switzerland
[b] Human Performance Lab, Schulthess Clinic, Zurich, Switzerland

A R T I C L E I N F O

Article history:
Received 28 September 2018
Received in revised form
11 June 2019
Accepted 19 June 2019

Keywords:
Muscle activity
Hamstring
Foot rotation
ACL reconstruction

A B S T R A C T

Objectives: To investigate the influence of internal and external foot rotation on medial and lateral hamstring electromyographic (EMG) activity during conventional hamstring exercises in patients following anterior cruciate ligament (ACL) reconstruction.
Design: Cross-sectional study.
Setting: EMG activity of medial and lateral hamstrings was recorded during prone leg curl, single-leg bridge and Nordic hamstring exercises with three different foot positions (neutral, internal rotation, external rotation), randomly presented.
Participants: Twenty patients 9–15 months after ACL reconstruction with the semitendinosus-gracilis graft.
Main outcome measures: Concentric and eccentric EMG activity normalized to the EMG activity recorded during a maximal voluntary contraction (MVC).
Results: Compared to the neutral position, the EMG activity of the medial hamstring during prone leg curl exercise was significantly increased by internal foot rotation (concentric: +8.7% MVC; eccentric: +5.9% MVC; $p < 0.01$; $d = 0.88–0.99$) and decreased by external rotation (concentric: 5.8% MVC; eccentric: 5.2% MVC; $p < 0.05$; $d = 0.67–0.92$). Foot position did not significantly affect hamstring EMG activity during single-leg bridge and Nordic hamstring exercises.
Conclusions: Active internal rotation of the foot during prone leg curl exercise can help selectively maximize muscle activity of the medial hamstring portion. This may have implications for post-operative rehabilitation of ACL patients with a semitendinosus-gracilis graft.

1. Introduction

Reconstruction of the anterior cruciate ligament (ACL) with an autologous semitendinosus-gracilis graft is one of the most commonly used and successful surgical approaches for the treatment of a ruptured ACL (Samuelsen, Webster, Johnson, Hewett, & Krych, 2017; Xie et al., 2015). However, chronic alterations in hamstring muscle function (weakness) and mass (atrophy) are common complications that are not easily resolved even following post-operative rehabilitation (Abourezk et al., 2017; Snow, Wilcox, Burks, & Greis, 2012; Viola, Sterett, Newfield, Steadman, & Torry, 2000). For example, knee flexor and internal rotator weakness (Armour et al., 2004) as well as semitendinosus atrophy (Snow et al., 2012) often manifest following ACL reconstruction with the semitendinosus-gracilis graft (Konrath et al., 2016), essentially because of a selective impairment of the medial hamstring segment induced by the semitendinosus tendon harvesting. In fact, besides their role of hip extensors, the function of the hamstring muscles at the knee joint is usually described as flexion and internal rotation for the medial muscle portion (i.e., semitendinosus and semimembranosus) and flexion and external rotation for the lateral portion (i.e., biceps femoris long and short heads) (Buford, Ivey, Nakamura, Patterson, & Nguyen, 2001; Peterson Kendall, Kendall McCreary, Geise Provance, McIntyre Rodgers, & Romani, 2005). Thus, it is important to explore clinical solutions that target medial hamstring (MH) activity in the context of post-operative

* Corresponding author..
E-mail address: andre_beuchat@hotmail.com (A. Beuchat).

https://doi.org/10.1016/j.ptsp.2019.06.010
1466-853X/

rehabilitation. In doing so, clinicians will better understand how to minimize activity early (for "protecting") and maximize activity later in rehabilitation toward better restoration of hamstring muscle function following ACL reconstruction with the semitendinosus-gracilis graft.

One simple and clinically-applicable strategy to modify the activity pattern of the MH and lateral hamstring (LH) is foot rotation. In healthy people, internal foot rotation has been shown to increase MH electromyographic (EMG) activity, while external rotation has been demonstrated to decrease MH activity and increase LH activity (Jonasson, Helgason, Ingvarsson, Kristjansson, & Briem, 2016; Lynn & Costigan, 2009; Mohamed, Perry, & Hislop, 2003). Comparable results have been observed in patients with knee osteoarthritis during walking with internally and externally rotated feet (Hubley-Kozey, Deluzio, Landry, McNutt, & Stanish, 2006; Lynn & Costigan, 2008). However, it remains unknown if the activity of the MH portion could also be selectively modified by internal/external foot rotation in patients following ACL reconstruction with a semitendinosus-gracilis graft. This knowledge would help in the identification of the exercises and conditions allowing for an optimal loading of the involved semitendinosus muscle in post-operative rehabilitation. For example, maximizing MH activity by means of internal foot rotation during ordinary hamstring exercises may be interesting in the late stages of rehabilitation. Therefore, the main objective of this study was to investigate the effect of foot rotation (internal and external rotation with respect to a neutral position) on the EMG activity of MH and LH during conventional rehabilitation exercises in patients following ACL reconstruction with the semitendinosus-gracilis graft.

2. Methods

2.1. Patients

The inclusion criteria were: age comprised between 18 and 50 years, ACL reconstruction with a semitendinosus-gracilis graft (no revision), at least 9 months post-surgery (which corresponds to a late rehabilitation stage), and signed written informed consent. The exclusion criteria were: previous knee surgeries (other than ACL reconstruction) and persistent knee pain on either side during knee flexion and daily activities. A convenience sample of 20 patients was recruited for the study (16 men). Their mean ± SD age, weight and height was 30 ± 9 years, 81 ± 14 kg and 180 ± 9 cm, respectively. The operated side was the right for five patients and the left for 15 patients. Nine patients had concomitant surgical procedures including meniscectomy (four patients) and meniscal repair (five patients). The mean time after surgery was 11 ± 1 months (range: 9–15 months). All patients were naive as to the purpose of the study. They all signed an informed consent form prior to data collection, and the project was approved by the local ethical committee (BASEC-Nr. 2017–00799).

2.2. Experimental design

For this cross-sectional study all patients completed a single testing session lasting 60–70 min. They first filled out the Tegner activity scale (0 = lowest activity level; 10 = highest activity level) (Wirth, Meier, Koch, & Swanenburg, 2013) and the knee outcome survey for activities of daily living scale (KOS-ADLS; 0% = highest disability; 100% = no disability) (Bizzini & Gorelick, 2007). After skin preparation for EMG recording (see below for details) and a general warm up (5 min cycling on an ergometer at a self-selected workload), patients completed several maximal voluntary contractions (MVC) for EMG normalization purposes. The ensuing experimental phase consisted in the realization of three different rehabilitation exercises (prone leg curl, single-leg bridge, Nordic hamstring), each with three different foot positions (neutral, internal and external foot rotation) during which EMG activity of MH and LH muscles as well as knee joint range of motion were concomitantly recorded on the operated side. The dependent variables were MH and LH EMG activity recorded during the concentric and eccentric phase of each exercise as well as medial activity ratio, while the independent variable was foot position.

2.3. EMG activity and goniometry

The skin was shaved with a razor and carefully cleaned with alcohol before electrode placement. Pairs of silver chloride, circular (recording diameter: 10 mm) surface electrodes were positioned over semitendinosus (MH) and biceps femoris (LH) muscle bellies according to SENIAM recommendations (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000), with an inter-electrode distance of 20 mm (see Fig. 1A). The EMG signal was amplified (gain: 1000), band-pass filtered (10–500 Hz) and recorded at a sampling frequency of 1000 Hz by means of wireless sensors (Myon, Schwarzenberg, Switzerland).

The knee joint angle was recorded using a twin-axis electronic goniometer (model TSD130, BIOPAC Systems, Inc., Goleta, CA, USA). The proximal arm of the goniometer was aligned with the lateral midline of the femur using the greater trochanter for reference (see Fig. 1A). The distal arm of the goniometer was aligned with the lateral midline of the fibula using the lateral malleolus for reference. The goniometer was attached to the skin using double-sided surgical tape and further secured with single-side tape. Knee joint angle data was sampled at 1000 Hz and synchronized with the EMG signal (see Fig. 1C for representative traces).

2.4. Maximal voluntary contractions

The maximal EMG activity signal of MH and LH muscles was required for normalization purposes. Therefore, knee flexor MVCs were realized for the operated side on a prone leg curl machine at an intermediate knee flexion angle of 60°, where none of the hamstring muscles shows a greater relative contribution to knee flexion torque (Onishi et al., 2002). The resistance was provided (manually) by the investigator. Patients first completed two submaximal familiarization trials (approximately 50–80% of their estimated MVC) followed by three MVC trials, during which they were instructed to build up force progressively and then maintain a maximal effort for 3–4 s. Rest intervals of 30 s were interspersed between consecutive trials. The same investigator provided standardized verbal commands and encouragement, to assist the patients in achieving maximal effort for every contraction.

2.5. Hamstring exercises

We selected three hamstring exercises that are commonly used for rehabilitation after ACL reconstruction: the prone leg curl, single-leg bridge and Nordic hamstring exercises. Patients completed each of the three exercise types with three different foot positions: internal rotation, neutral position and external rotation. The order of the three exercise types was first randomized, and then for each exercise type the three foot positions were randomly presented (patients had to complete the three foot positions prior to changing exercise). For each exercise, patients completed three-to-five consecutive familiarization trials followed by five consecutive (except for the Nordic hamstring exercise, for which single repetitions were separated by 2-min rest periods) experimental trials per foot position. Patients were asked to rotate the foot in maximal external or internal rotation or to hold it in a self-selected

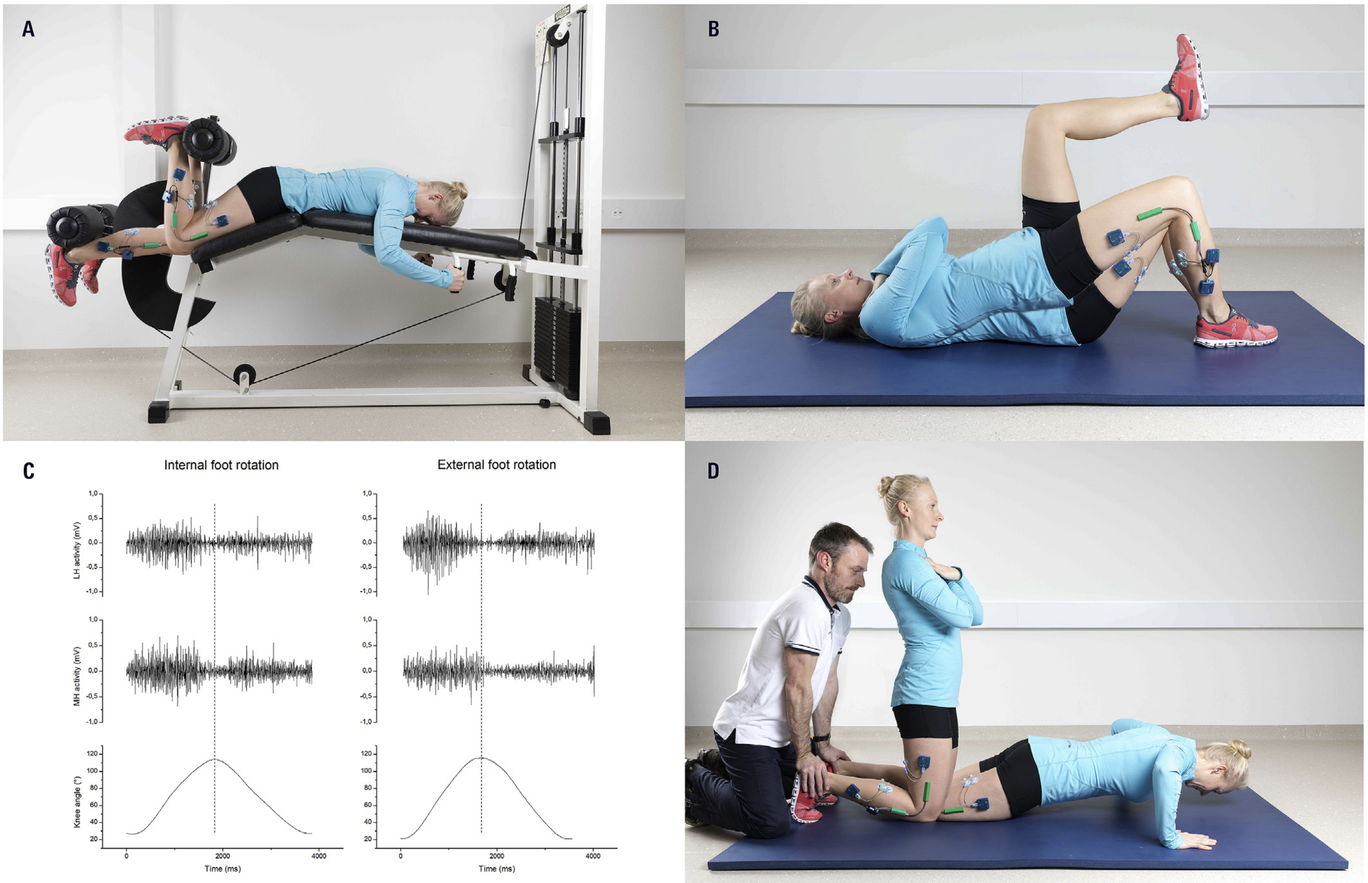

Fig. 1. The three hamstring exercises are shown, with respective starting and ending positions: A: prone leg curl, B: single-leg bridge, D: Nordic hamstring. C, representative concentric and eccentric EMG activity traces recorded with the foot internally and externally rotated. LH: lateral hamstring; MH: medial hamstring. The vertical lines indicate the transition between the concentric and eccentric phase of the exercise.

neutral position for the concentric and eccentric phases of respective exercises. The investigator visually monitored the foot position throughout the experimental trials. Patients benefited of 5 min of passive recovery between each exercise set.

2.5.1. - Prone leg curl

Patients were lying in the prone position in a commercially-available leg curl machine (Isotonic line, Technogym, Gambettola, Italy). The exercise was executed by both limbs simultaneously, starting with the knees fully extended (0° of flexion) and the hips in 10° of flexion (Fig. 1A). The position of the resistance pad was about 2 cm above the intermalleolar axis. Patients flexed the knee joints to an angle of ~100° (concentric phase) and subsequently lowered the weight again by resisting to knee extension (eccentric phase). The hip angle was constant throughout the exercise. Movement speed was dictated by a metronome set to 40 beats/min (0.67 Hz), which resulted in concentric and eccentric phase durations of ~1.5 s each. The resistance was self-selected by each patients as a load that could be comfortably lifted for ~15 repetitions. The mean ± SD load was 10.5 ± 3.2 kg (range: 5–15 kg).

2.5.2. - Single-leg bridge

Patients were lying in the supine position on an exercise mat. The exercise was executed by the operated limb only, starting with the hip and knee joints flexed at ~45° and 100°, respectively, and the foot flat on the floor (Fig. 1B). The contralateral lower limb was maintained at 90° of hip flexion and 90° of knee flexion. Patients were asked to cross their arms over the chest to minimize compensatory strategies (Lehecka et al., 2017). They were instructed to lift the pelvis upward to full hip extension (concentric phase), and subsequently lower their body again (eccentric phase). Knee range of motion was approximately 15° (from ~100° to 85° of flexion). Movement speed was dictated by a metronome set to 60 beats/min (1 Hz), which resulted in concentric and eccentric phase durations of ~1 s each.

2.5.3. - Nordic hamstring

Patients were kneeling on an exercise mat. The exercise was executed by both limbs simultaneously, starting with the hips fully extended (0° of flexion), the knees flexed at ~80° and the ankle joints at ~90° (Fig. 1D). The arms were crossed over the chest. Patients were instructed to resist a controlled forward-falling motion of their body for as long as possible using their hamstrings. The instructions also included to hold the hips fully extended during the whole movement. Knee range of motion was approximately 75° (from ~80° to 5° of flexion). The feet were stabilized to the floor by the investigator. Patients used their upper limbs to dampen the movement and regained the starting position with a push up action. Consequently, only the eccentric phase of the exercise was considered. Movement speed was not regulated by a metronome but was self-imposed.

2.6. Data analysis

The mean root mean square amplitude of the EMG signal of each muscle was computed separately for the concentric and eccentric phases of each repetition. The onset and offset of the concentric and eccentric phases were defined visually using the goniometric signal (see Fig. 1C). These root mean square values obtained during the different exercises were normalized to the root mean square values for a 500-ms window centered around the highest root mean square from MVC trials, to provide the mean EMG activity of MH and LH muscles (% MVC). In order to emphasize a possible “overactivation” (or “underactivation”) of the MH muscle with respect to the LH, the medial activity ratio was calculated for each condition using this formula: EMG activity of MH/(EMG activity of MH + LH). A medial activity ratio of 0.5 would indeed demonstrate a comparable EMG activity for the two muscles, while a ratio >0.5 would reveal a greater EMG activity of the MH muscle with respect to the LH.

2.7. Statistical analyses

Concentric and eccentric EMG activity of the MH and LH muscles recorded during the prone leg curl, single-leg bridge and Nordic hamstring exercises as well as respective medial activity ratios were examined with one-way repeated measures ANOVAs using foot position (neutral, internal rotation, external rotation) as the independent variable. Tukey's post-hoc comparisons between internal/external rotation and neutral were performed in case of significant main effect. The level of significance was set at $p < 0.05$. In addition, effect sizes (Cohen's “d”) were calculated using G*Power software to assess the magnitude of the differences for each comparison. Effect sizes were classified as small if $d = 0.2$, medium if $d = 0.5$ and large if $d \geq 0.80$ (Cohen, 1988).

3. Results

All data from all twenty patients were included in the analyses. The mean Tegner activity scale and KOS-ADLS scores were respectively 6 ± 1 points and 93 ± 1%.

3.1. Prone leg curl

Representative concentric and eccentric EMG activity traces recorded for the prone leg curl exercise with the foot internally vs. Externally rotated are depicted in Fig. 1C. For the MH muscle, both concentric (Table 1) and eccentric (Table 2) EMG activity was significantly higher in internal rotation than in neutral ($p = 0.002$ and $p < 0.001$, respectively), and significantly lower in external rotation than in neutral ($p = 0.023$ and $p = 0.002$, respectively), with medium to large effect sizes (d range: 0.67–0.99). For the LH muscle, both concentric (Table 1) and eccentric (Table 2) EMG activity was significantly higher in external rotation than in neutral ($p = 0.012$ and $p = 0.034$, respectively), with medium effect sizes ($d = 0.71$ and $d = 0.62$, respectively). Eccentric EMG activity of the LH muscle was also significantly lower in internal rotation than in neutral ($p = 0.001$), with a large effect size ($d = 0.95$). As a consequence, medial activity ratios obtained in both concentric (Fig. 1A) and eccentric (Fig. 2A) conditions were significantly higher in internal rotation than in neutral ($p = 0.001$ and $p < 0.001$, respectively) and significantly lower in external rotation than in neutral (both $p < 0.001$), with large effect sizes (d range: 1.13–1.17).

3.2. Single-leg bridge

Concentric and eccentric EMG activity of MH and LH muscles (Tables 1 and 2) for the single-leg bridge exercise as well as respective medial activity ratios (Figs. 2B and 3B) were not significantly affected by foot position.

3.3. Nordic hamstring

Eccentric EMG activity of MH and LH muscles (Table 2) for the Nordic hamstring exercise as well as respective medial activity ratios (Fig. 3C) were not significantly affected by foot position.

4. Discussion

The main findings of this study are that, with respect to a neutral position, internal foot rotation increased the absolute (% MVC) and relative (medial activity ratio) activity of the MH muscle during the concentric and eccentric phases of prone leg curl exercise in patients following ACL reconstruction with the semitendinosus-gracilis graft. In the same way, external foot rotation during leg curl exercise decreased MH and increased LH concentric and eccentric EMG activity. Contrary to the results observed for leg curl exercise, internal and external foot rotation had no effect on hamstring EMG activity for single-leg bridge and Nordic hamstring exercises.

In healthy subjects, internal rotation has been shown to increase MH activity (and vice versa for external rotation) during common hamstring exercises (Lynn & Costigan, 2009) and isometric knee flexion (Jonasson et al., 2016; Mohamed et al., 2003). The present study is the first looking at the influence of foot rotation on hamstring muscle activity during conventional rehabilitation exercises in patients who have undergone ACL reconstruction. We confirm here that hamstring EMG activity is increased in the same direction as foot rotation (MH for internal and LH for external rotation), but only for the prone leg curl exercise. Because the amplitude of the EMG signal – despite limitations – can be used to infer on motor unit behavior, the increases in EMG activity observed here could be interpreted as the result of increased semitendinosus motor unit recruitment and/or discharge rate. The most likely explanation for this rotation-induced facilitation of hamstring EMG activity is linked with its often-neglected role in producing transverse plane rotations at the knee joint. Along with their common function of knee flexors on the sagittal plane, the MH

Table 1
Concentric EMG activity of MH and LH muscles by exercise and foot position.

	MH (mean ± SD)	Mean difference (95% CI)	LH (mean ± SD)	Mean difference (95% CI)
Prone leg curl				
Internal (% MVC)	61.2 ± 15.6	8.7 (2.9–14.4)*	48.8 ± 21.2	−5.1 (−10.8 to 0.7)
Neutral (% MVC)	52.6 ± 15.7		53.9 ± 18.6	
External (% MVC)	46.8 ± 16.8	−5.8 (−10.9 to −0.7)*	65.5 ± 22.0	11.6 (2.3–20.9)*
Single-leg bridge				
Internal (% MVC)	45.9 ± 17.7	2.7 (−4.1 to 9.5)	48.6 ± 23.6	−2.0 (−8.4 to 4.5)
Neutral (% MVC)	43.1 ± 18.2		50.5 ± 26.2	
External (% MVC)	42.6 ± 16.6	−0.6 (−6.2 to 5.0)	53.3 ± 25.3	2.8 (−4.5 to 10.2)

Mean difference with respect to neutral. *different from neutral ($p < 0.05$). CI = confidence interval; LH = lateral hamstring; MH = medial hamstring; MVC = maximal voluntary contraction.

Table 2
Eccentric EMG activity of MH and LH muscles by exercise and foot position.

	MH (mean ± SD)	Mean difference (95% CI)	LH (mean ± SD)	Mean difference (95% CI)
Prone leg curl				
Internal (% MVC)	37.9 ± 14.0	5.9 (2.4–9.4)*	31.3 ± 13.5	−5.3 (−8.6 to −2.0)*
Neutral (% MVC)	32.0 ± 12.4		36.6 ± 13.7	
External (% MVC)	26.9 ± 11.9	−5.2 (−8.4 to −1.9)*	41.9 ± 14.2	5.3 (0.3–10.4)*
Single-leg bridge				
Internal (% MVC)	37.9 ± 16.7	0.9 (−3.1 to 4.8)	41.3 ± 22.1	−1.9 (−7.4 to 3.7)
Neutral (% MVC)	37.1 ± 16.7		43.2 ± 23.9	
External (% MVC)	37.1 ± 14.8	0.0 (−4.1 to 4.2)	45.2 ± 21.0	2.0 (−3.4 to 7.4)
Nordic hamstring				
Internal (% MVC)	48.8 ± 33.5	−1.8 (−6.7 to 3.0)	51.9 ± 19.6	−1.3 (−6.2 to 3.6)
Neutral (% MVC)	50.7 ± 29.9		53.2 ± 16.4	
External (% MVC)	51.1 ± 25.4	0.5 (−4.9 to 5.8)	56.7 ± 18.6	3.5 (−0.6 to 7.6)

Mean difference with respect to neutral. *different from neutral ($p < 0.05$). CI = confidence interval; LH = lateral hamstring; MH = medial hamstring; MVC = maximal voluntary contraction.

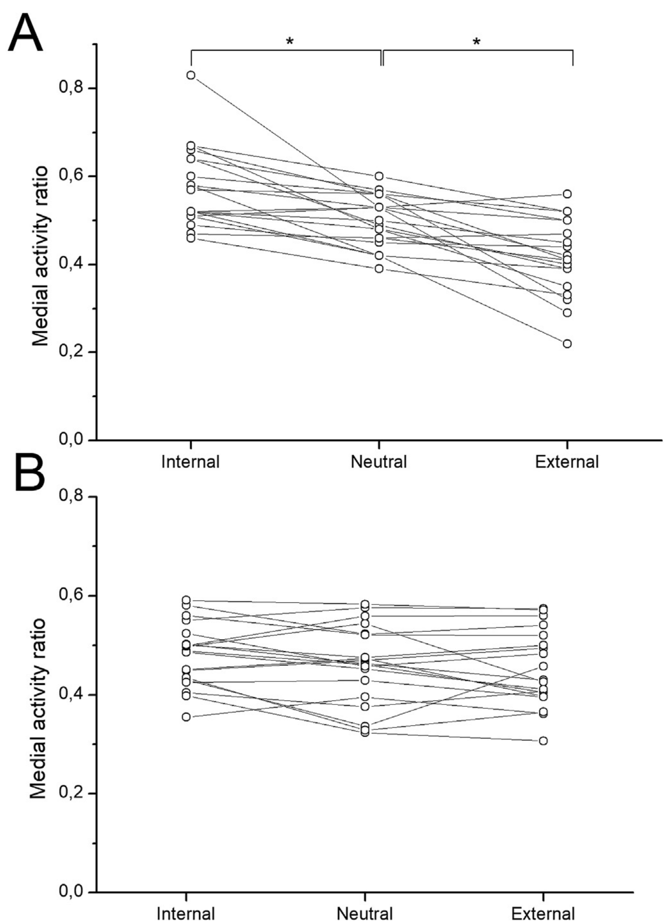

Fig. 2. Medial activity ratio by foot position for the concentric phase of prone leg curl (A) and single-leg bridge (B) exercises. *significant difference at $p < 0.05$.

and LH also produce internal and external rotation at the knee, respectively (Buford et al., 2001; Peterson Kendall et al., 2005). The patients tested in our study actively rotated their foot prior to performing the leg curl exercise and then hold it actively rotated during the execution of the exercise, which selectively increased the EMG activity of one of the two hamstring portions due to their respective combined action of knee flexors and rotators. Interestingly, foot rotation opposite to the action of respective muscles, and more particularly external rotation, resulted in a facilitatory-inhibitory interplay between the LH and MH muscles.

We observed a notable effect of foot rotation on hamstring EMG activity for the prone leg curl exercise but not for the single-leg bridge and Nordic hamstring exercises. There are several differences between the exercise setups that could have influenced these EMG activity results. For example, knee range of motion and exercise intensity were quite dissimilar between the leg curl (highest range of motion and large inter-individual variability in load), bridge (lowest range of motion with considerable contribution from other joints) and Nordic (highest intensity, which may have led to ceiling effects) exercises, while these features were actually equivalent for the main comparisons between foot positions (within each exercise). Probably the main reason for these differences in EMG facilitation between the exercise types is related to foot control during actual execution. The foot was free to move only for the prone leg curl exercise while it was restrained by the floor (single-leg bridge) or the investigator (Nordic hamstring) in the other conditions. This implies that for the prone leg curl exercise the rotation of the foot was realized actively. For the single-leg bridge exercise the foot was rotated actively before the exercise, but during the actual execution the foot was flat on the floor and in this way, it was passively restrained and no additional hamstring activity was required to maintain the rotated position. Similarly, for the Nordic hamstring exercise the feet were fixed on the floor by the investigator, which imposed a passive foot rotation. Consequently, for both of these exercises the hamstring muscles were primarily activated in their role of knee flexors but not, or minimally, as knee rotators. One possible adaptation of the Nordic hamstring exercise could be to kneel on a box with the feet hanging free over the edge of the box, so that internal/external rotation can be actively maintained. In the same way, the single-leg bridge exercise could potentially be realized with only the calcaneus in contact with the floor and the foot dorsiflexed, a common exercise variation, so that internal/external rotation can be actively maintained.

Restoring hamstring muscle function in patients who have undergone ACL reconstruction with a semitendinosus-gracilis graft is a big challenge, particularly because of the harvested semitendinosus tendon. Although this surgical procedure is quite straightforward and successful, it provokes neuromuscular alterations such as knee flexor weakness (Huber et al., 2019) and semitendinosus atrophy (Snow et al., 2012) that are not resolved even years after surgery. Therefore, from a rehabilitation perspective it is important to find solutions for selectively unloading (early stages of rehabilitation) or overloading (late stages of rehabilitation) the semitendinosus muscle, whose voluntary control cannot be dissociated from the other hamstring muscles. According to our EMG results, realizing the prone leg curl exercise with active internal

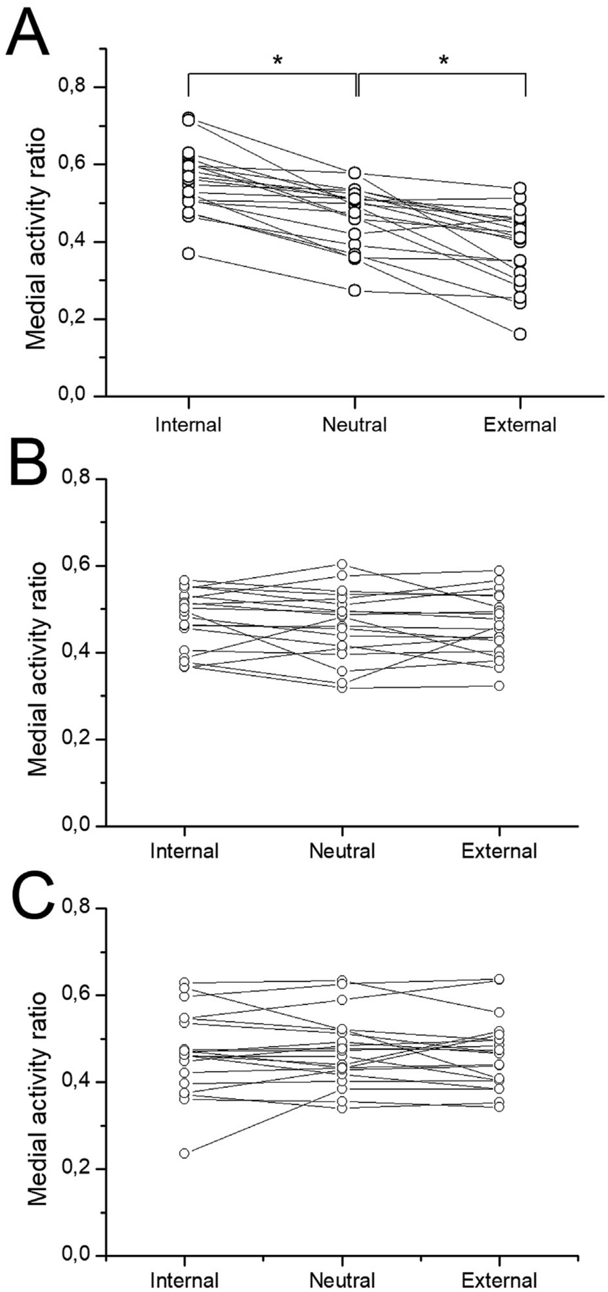

Fig. 3. Medial activity ratio by foot position for the eccentric phase of prone leg curl (A), single-leg bridge (B) and Nordic hamstring (C) exercises. *significant difference at $p < 0.05$.

rotation of the foot and a self-selected load (which is straightforward and patient-friendly but not necessarily the most effective solution) is a valid option to maximize semitendinosus activity, thus presumably loading, and vice versa for external foot rotation. Because weight, knee range of motion and hip/body position (e.g., standing vs. lying prone) can be easily manipulated for the leg curl exercise, this offers additional opportunities to the physical therapist to optimize post-operative rehabilitation in this patient population.

In the present study, the setup and exercise selection were as close as possible to the clinical practice. We decided to consider conventional exercises with a concentric and eccentric phase because it is the most common way to realize these exercises, but we did not include isometric conditions that are also ordinary, particularly in the early stages of rehabilitation. Patients were asked to maximally rotate the foot before the exercise, but the amount of foot rotation was not measured nor standardized. The changes in hamstring EMG activity we observed remain therefore to be verified at intermediate foot rotation positions. In this cross-sectional study, we only demonstrated acute changes in hamstring EMG activity induced by foot rotation. The next logical step would be to determine the clinical utility of these findings with a longitudinal intervention study designed to evaluate the effects of combined knee flexion + internal rotation exercises vs. knee flexion only or internal rotation only on hamstring neuromuscular function.

5. Conclusion

The present study demonstrated that active internal rotation of the foot during prone leg curl exercise increased the absolute and relative activity of the MH muscles in patients who underwent ACL reconstruction with the semitendinosus-gracilis graft. Further investigation is needed to confirm the real clinical value of these findings.

Conflicts of interest

None declared.

Ethical statements

Written informed consent and permission to use information was obtained from the patients.

Funding

None declared.

Acknowledgments

The authors thank the patients for their dedication during the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2019.06.010.

References

Abourezk, M. N., Ithurburn, M. P., McNally, M. P., Thoma, L. M., Briggs, M. S., Hewett, T. E., et al. (2017). Hamstring strength asymmetry at 3 Years after anterior cruciate ligament reconstruction alters knee mechanics during gait and jogging. *The American Journal of Sports Medicine, 45*, 97–105.

Armour, T., Forwell, L., Litchfield, R., Kirkley, A., Amendola, N., & Fowler, P. J. (2004). Isokinetic evaluation of internal/external tibial rotation strength after the use of hamstring tendons for anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine, 32*, 1639–1643.

Bizzini, M., & Gorelick, M. (2007). Development of a German version of the knee outcome survey for daily activities. *Archives of Orthopaedic and Trauma Surgery, 127*, 781–789.

Buford, W. L., Jr., Ivey, F. M., Jr., Nakamura, T., Patterson, R. M., & Nguyen, D. K. (2001). Internal/external rotation moment arms of muscles at the knee: Moment arms for the normal knee and the ACL-deficient knee. *The Knee, 8*, 293–303.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Earlbaum Associates.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology, 10*, 361–374.

Huber, R., Viecelli, C., Bizzini, M., Friesenbichler, B., Dohm-Acker, M., Rosenheck, T., et al. (2019). Knee extensor and flexor strength before and after anterior cruciate ligament reconstruction in a large sample of patients: Influence of graft

type. *The Physician and Sportsmedicine, 47*, 85–90.
Hubley-Kozey, C. L., Deluzio, K. J., Landry, S. C., McNutt, J. S., & Stanish, W. D. (2006). Neuromuscular alterations during walking in persons with moderate knee osteoarthritis. *Journal of Electromyography and Kinesiology, 16*, 365–378.
Jonasson, G., Helgason, A., Ingvarsson, T., Kristjansson, A. M., & Briem, K. (2016). The effect of tibial rotation on the contribution of medial and lateral hamstrings during isometric knee flexion. *Sport Health, 8*, 161–166.
Konrath, J. M., Vertullo, C. J., Kennedy, B. A., Bush, H. S., Barrett, R. S., & Lloyd, D. G. (2016). Morphologic characteristics and strength of the hamstring muscles remain altered at 2 Years after use of a hamstring tendon graft in anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine, 44*, 2589–2598.
Lehecka, B. J., Edwards, M., Haverkamp, R., Martin, L., Porter, K., Thach, K., et al. (2017). Building a better gluteal bridge: Electromyographic analysis of hip muscle activity during modified single-leg bridges. *Int J Sports Phys Ther, 12*, 543–549.
Lynn, S. K., & Costigan, P. A. (2008). Effect of foot rotation on knee kinetics and hamstring activation in older adults with and without signs of knee osteoarthritis. *Clinical Biomechanics, 23*, 779–786.
Lynn, S. K., & Costigan, P. A. (2009). Changes in the medial-lateral hamstring activation ratio with foot rotation during lower limb exercise. *Journal of Electromyography and Kinesiology, 19*, e197–e205.
Mohamed, O., Perry, J., & Hislop, H. (2003). Synergy of medial and lateral hamstrings at three positions of tibial rotation during maximum isometric knee flexion. *The Knee, 10*, 277–281.
Onishi, H., Yagi, R., Oyama, M., Akasaka, K., Ihashi, K., & Handa, Y. (2002). EMG-angle relationship of the hamstring muscles during maximum knee flexion. *Journal of Electromyography and Kinesiology, 12*, 399–406.
Peterson Kendall, F., Kendall McCreary, E., Geise Provance, P., McIntyre Rodgers, M., & Romani, W. A. (2005). *Muscles: Testing and function with posture and pain* (5th ed.). Lippincott Williams & Wilkins.
Samuelsen, B. T., Webster, K. E., Johnson, N. R., Hewett, T. E., & Krych, A. J. (2017). Hamstring autograft versus patellar tendon autograft for ACL reconstruction: Is there a difference in graft failure rate? A meta-analysis of 47,613 patients. *Clinical Orthopaedics and Related Research, 475*, 2459–2468.
Snow, B. J., Wilcox, J. J., Burks, R. T., & Greis, P. E. (2012). Evaluation of muscle size and fatty infiltration with MRI nine to eleven years following hamstring harvest for ACL reconstruction. *J Bone Joint Surg Am, 94*, 1274–1282.
Viola, R. W., Sterett, W. I., Newfield, D., Steadman, J. R., & Torry, M. R. (2000). Internal and external tibial rotation strength after anterior cruciate ligament reconstruction using ipsilateral semitendinosus and gracilis tendon autografts. *The American Journal of Sports Medicine, 28*, 552–555.
Wirth, B., Meier, N., Koch, P. P., & Swanenburg, J. (2013). [Development and evaluation of a German version of the Tegner activity scale for measuring outcome after anterior cruciate ligament injury]. *Sportverletzung - Sportschaden, 27*, 21–27.
Xie, X., Liu, X., Chen, Z., Yu, Y., Peng, S., & Li, Q. (2015). A meta-analysis of bone-patellar tendon-bone autograft versus four-strand hamstring tendon autograft for anterior cruciate ligament reconstruction. *The Knee, 22*, 100–110.