ABSTRACT

Introduction/Purpose: Previous studies have shown inhibition of previously injured hamstrings during eccentric exercises, but it is unknown whether this effect is also present during an isometric position-control exercise such as the single-leg Roman chair hold (SLRCH).

Methods: This cross-sectional study investigated muscle activation during the SLRCH in individuals with prior hamstring injuries. Twelve recreationally active male soccer players and athletes performed the SLRCH with a five-repetition maximum load. Muscle activation was assessed using the transverse relaxation (T2) time for the biceps femoris long and short heads (BFll and BFsl), semitendinosus (ST), semimembranosus, and adductor magnus and compared within and between legs. Muscle cross-sectional area (CSA) was also quantified.

Results: T2 times significantly increased for all muscles except the adductor magnus in both legs. In both legs, the ST showed a significantly larger increase in T2 time compared with all other muscles. The BFll showed a significantly smaller increase in T2 time in the injured leg compared with the uninjured leg (−7.1%), whereas there were no significant differences between legs for the other muscles. Muscle CSA for any of the muscles did not significantly differ between the injured and uninjured legs.

Conclusion: The ST was preferentially activated during the SLRCH in both the uninjured and injured legs, but the magnitude of preferential activation was smaller (~10%) than observed previously during eccentric exercises (~17%–30%). Furthermore, the BFll in the previously injured leg was activated less compared with the BFll in the uninjured leg, despite no differences in muscle CSA.

Keywords: Inhibition, Injury, Isometric, Magnetic resonance imaging, Pain, Strength training

INTRODUCTION

Hamstring injuries are one of the most common and severe injuries in sports that involve high-speed running, such as soccer and athletics. Pain and swelling during the initial stages of a hamstring injury can lead to corticospinal inputs to the motor cortex that may reduce the ability to activate the injured tissue. Although this inhibition might initially be beneficial to protect the injured tissue from further damage, it might also reduce the force production and, adaptations to training in the long term, which in turn may compromise performance and increase the risk of reinjury. Indeed, this inhibition can still be observed up to 18 months postinjury despite individuals training and competing at preinjury levels.

Neuromuscular hamstring inhibition has mostly been investigated during eccentric and concentric muscle actions and has primarily been observed to occur in the biceps femoris long head (BFll) during eccentric muscle actions performed at longer muscle-tendon unit lengths. One study investigated hamstring muscle activation in previously injured individuals during isometric knee flexions and observed a significantly lower activation during 20%, but not 50%, of the maximum voluntary contraction. This suggests higher-load isometric exercises may be used to train the hamstrings with less influence of inhibition. Pushing (i.e., force control) isometric muscle actions, such as knee flexion, however, exhibit different neural control strategies than holding (i.e., position control) isometrics, with the latter exhibiting more similarities in muscle activation to eccentric muscle actions. It remains unknown whether this similarity in neural control to eccentric actions makes position-control isometric exercises more prone to inhibition, in particular, when performed at a high intensity (e.g., >85% of one-repetition maximum). If isometric position-control exercises are characterized by no inhibition or smaller inhibition than eccentric exercises after injury, this suggests that position-control exercises may be particularly beneficial to implement during rehabilitation to optimize adaptations.

The single-leg Roman chair hold (SLRCH) is a popular isometric position-control exercise and can be used to investigate the presence...
of neuromuscular inhibition (11,12). Neuromuscular inhibition can be investigated by comparing muscle activation between injured and uninjured individuals, or injured and uninjured legs within the same individual, with the latter approach providing higher statistical power and similar validity because muscle activation in the uninjured leg is similar between the uninjured leg of injured individuals and completely injury-free individuals (5,9). Whereas muscle activation can be assessed by (high-density) surface electromyography (sEMG) or magnetic resonance imaging (MRI), MRI provides better spatial resolution than conventional sEMG, which cannot discriminate well between the BFsh and biceps femoris short head (BFsh) or the semimembranosus (SM) and semitendinosus (ST) (13–15). MRI has therefore been used to characterize muscle activation patterns during various exercises, including hamstring exercises (16–22). Specifically, MRI allows for the measurement of transverse relaxation ($T_2$) times that the BFsh of the injured leg would be activated less compared to uninjured individuals and found approximately equal activation of muscles during the SLRCH exercise in the uninjured leg. A previous study (22), with nonuniform changes in muscle morphology and architecture after training (5,15,16,18,20,22,24,25). A secondary aim of our study was, therefore, to compare muscle activation between different lower-limb muscles during the SLRCH exercise in the uninjured leg. A previous study investigated muscle activation during the single-leg supine bridge in uninjured individuals and found approximately equal activation of the lateral (here defined as the BFsh) and medial (here defined as the ST and/or SM) hamstrings (22,26). Because the supine bridge is largely similar to the SLRCH, we hypothesized that there would be no significant differences in muscle activation between the ST or SM and BFsh in the uninjured leg.

**METHODS**

**Study design**

This study used a repeated-measures design to investigate hamstrings muscle activation during the SLRCH exercise. Muscle activation during the exercise was investigated by determining differences in the exercise-induced increases in $T_2$ time after the exercise. All tests were performed within a period of approximately 6 months in the MRI Department of the Catholic University of Valencia. The study was prospectively registered on the Open Science Framework (https://osf.io/e6m32/) and was approved by the ethics committee of the Catholic University of Valencia (UCV/2021–2022/169). Participants were recruited via advertisements at the university and local sports clubs. Informed consent was obtained and the rights of subjects were protected.

**Participants and sample size calculation**

Twelve males (mean ± standard deviation [SD] age, 23.8 ± 2.0 years; mass, 72.8 ± 3.3 kg; and height, 176.8 ± 3.9 cm) who were recreationally participating in running-based sports (i.e., soccer and sprinting) at least three times per week and between 18 and 35 years old participated. All participants were required to have a history of a unilateral hamstring strain injury within the previous 12 months but to be fully active at their chosen sport at the time of testing. Participants were excluded if their body mass index was outside 18–25 or if they had any known cardiovascular or other health conditions (e.g., diabetes).

All participants were asked to fill out a questionnaire with their age, gender, limb dominance, and type of sports participation. Height and weight were determined using standard procedures. The participants were also required to fill out a questionnaire with their chosen physiotherapist who diagnosed and treated them. In line with previous studies (5,6), the notes from the clinical examination were used to determine the date of injury, return to preinjured levels of training and competition, severity, location, and rehabilitation details. All participants also completed a standard MRI screening questionnaire. Seven individuals had a unilateral injury of the BFsh within the previous 12 months, with the ST being involved in four individuals and no information was available for one individual. The participants had no history of other major injuries. Participants were instructed to maintain their habitual diet (including caffeine intake) the day before the measurements. All measurements were performed in the morning.

Sample size was estimated a priori as detailed in Supplemental Content 1 (http://links.lww.com/EM9/A13).

**Exercise protocol**

To ensure the accuracy of $T_2$ measures, participants were instructed to avoid strength training or strenuous activity of the lower limbs for 5 days before the experimental session and were seated for 15–30 min before preexercise imaging in line with previous studies (22,24). Participants completed one familiarization session under the supervision of a researcher before the test session (Supplemental Content 1, http://links.lww.com/EM9/A13). Functional MRI scans of the thighs of both legs were acquired before and immediately after the exercise. The exercise was performed in a room adjacent to the MRI scanner to minimize the time between the exercise and the start of the scan (which was <2 min) because exercise-induced $T_2$ changes have a half-life of ∼7 min (23). All participants were seated in a wheelchair for transfer to the MRI scanner to minimize non-exercise-related hamstrings activation.

Both the previously injured and uninjured legs performed five sets of five repetitions (88% 1RM) of 3–5 s of the SLRCH exercise (Supplemental Content 1, http://links.lww.com/EM9/A13) per the previously described protocol (12,27). Briefly, the participants were positioned with the face toward the ground, the spine iliaca anterior superior supported by a pelvic pad, the knees in slight flexion, and the feet secured under a foot pad. Participants were then asked to raise their trunk upward until the trunk was approximately parallel to the ground and subsequently hold this position using one of the legs with the contralateral leg above the pad to ensure a single-leg condition. This position was held for approximately 3–5 s to achieve an isometric condition of the hamstrings (12,27). The leg was then alternated to provide ~3–5 s of stimulus to the other leg. A rest period of 2 min was provided between sets during which the participants were seated in a chair placed next to the Roman chair to minimize hamstring activation. The order in which the legs were measured was randomized, and the contralateral leg was rested on top of the pads.

**MRI protocol**

All MRI measurements were performed using a 3-tesla whole-body imager with surface phased-array coils (Philips Achieva, Eindhoven, Netherlands). The primary aim of our study was, therefore, to investigate whether the BFsh in a previously injured leg is activated less compared with the BFsh in the same individual’s uninjured leg as determined by exercise-induced increases in $T_2$ time. Because holding isometric muscle actions, such as the SLRCH, have been shown to exhibit similarities in muscle activation to eccentric muscle actions (10), we hypothesized that the BFsh of the injured leg would be activated less compared with the uninjured leg. Furthermore, knowledge about the absolute and relative activation of different muscles in the uninjured leg during this exercise may help practitioners determine more effective exercise prescription because (relative) muscle activation has been associated with nonuniform changes in muscle morphology and architecture after training (5,15,16,18,20,22,24,25). A secondary aim of our study was, therefore, to compare muscle activation between different lower-limb muscles during the SLRCH exercise in the uninjured leg. A previous study investigated muscle activation during the single-leg supine bridge in uninjured individuals and found approximately equal activation of the lateral (here defined as the BFsh) and medial (here defined as the ST and/or SM) hamstrings (22,26). Because the supine bridge is largely similar to the SLRCH, we hypothesized that there would be no significant differences in muscle activation between the ST or SM and BFsh in the uninjured leg.
the Netherlands) as described previously and further detailed in Supplemental Content 1 (http://links.lww.com/EM9/A13) (20,24). The same imaging procedures and sequences were applied before and immediately after exercise.

**Data analysis**

All MRI scans were transferred to a computer to determine the T<sub>2</sub> time and muscle cross-sectional area (CSA) as detailed in Supplemental Content 1 (http://links.lww.com/EM9/A13). Briefly, a circular region of interest (ROI) was placed in each muscle (BF<sub>lh</sub> and BF<sub>sh</sub>, ST, SM, and adductor magnus [AM]) in each of the T<sub>2</sub> mapping images with use of the fat-suppressed images using image analysis software (Olea Sphere; Olea Medical, La Ciotat, France). These ROIs were placed in a homogeneous region of contractile tissue (avoiding fat, aponeurosis, tendon, bone, and blood vessels), and great care was taken to replicate the ROI placements in the pre- and postexercise images. An MRI technician who was experienced with MRI image analysis placed all ROIs.

Muscle CSA was also determined in each preexercise T<sub>2</sub>-weighted image (Fig. 1) to assess differences in muscle CSA in the injured and uninjured legs. To this purpose, the muscle boundaries were manually traced in each cross-section. Muscle CSA was compared by determining the average area within each scan and comparing the averages between legs. A second examiner (I.J.B.) placed ROIs in a random selection of nine individuals (total of 343 cross-sections) to assess interrater reliability.

**Statistical analysis**

All statistical analyses were performed using SPSS Version 25.0.0.1 (IBM Corporation, Chicago, IL, USA). A repeated-measures linear-mixed model fitted with a restricted maximum likelihood method was used to compare percentage change in T<sub>2</sub> times between muscles in each leg. The difference in the change score was used to compare T<sub>2</sub> times between the muscles in the injured and uninjured legs. Similarly, the difference in muscle CSA was used to compare CSAs between the legs. Muscle was specified as a fixed factor, with the region within each muscle being specified as a nested effect within muscle. Each participant was modeled to include a random intercept and slope with a variance components co-variate structure. Two-sided tests were performed for all comparisons, except for the difference in BF<sub>lh</sub> activation between legs for which a one-sided test was used in line with our directional hypothesis of lower activation in the injured leg. To correct for multiple comparisons, the α level for accepting statistical significance was adjusted to 0.05/5 = 0.01. Marginal means ± standard error (SE) with their corresponding 95% confidence intervals (CIs) were reported for all statistical analyses. Normality of the residuals was assessed with visual inspection of boxplots and Q-Q plots based on the average T<sub>2</sub> time or CSA of each muscle. Outliers were identified as data points >1.5 times the inter-quartile distance. Additional analyses were performed after removal of outliers to investigate the sensitivity of the findings.

The interobserver reliability for muscle CSA was determined using the mean rating (k = 2) two-way random model for absolute agreement intraclass correlation coefficient (ICC). The two-way random effects model was chosen to allow generalizability of the results to other raters with similar characteristics, the mean of k raters was used because multiple raters assessed the same CSA, and absolute agreement was used because we considered it important that the absolute results of different raters agree. The ICC was considered poor if <0.69, acceptable if 0.70–0.79, good if 0.80–0.89, and excellent if 0.90–0.99. The SE of measurement was calculated as the square root of the mean square error term from a repeated-measures analysis of variance.

**RESULTS**

The mean ± SD number of days between injury and the experimental session was 226 ± 66. The mean ± SD rehab duration was 50 ± 34 days. None of the participants reported pain during performance of the exercise session. The mean ± SD five-repetition maximum was 29.6 ± 4.5 kg. All participants had right-leg dominance. Eight injuries occurred in the right leg and four in the left leg. Participants typically had sports practice twice a week with one competition on the weekend for soccer athletes and more sporadic competitions for the sprint athletes.

**Muscle activation within each leg**

Q-Q plots revealed deviations from normality for several of the outcomes. Log transformation did not substantially improve the

---

**Figure 1.** Cross-section (slice 7) with the transverse relaxation (T<sub>2</sub>) times for the previously injured and uninjured limbs of a single participant acquired immediately after the single-leg Roman chair protocol. The color spectrum illustrates the absolute T<sub>2</sub> value (ms), with blue and green areas depicting lower and higher relaxation times, respectively. Note the difference in T<sub>2</sub> times between the previously injured (right leg, left cross-section on image) and uninjured limbs, particularly for semitendinosus (ST) in this individual. Orange lines depict the cross-sectional areas (CSAs) for each muscle. The adductor magnus muscle boundaries could not accurately be determined and were, therefore, not included in the CSA analyses. BF<sub>lh</sub>, biceps femoris long head; BF<sub>sh</sub>, biceps femoris short head; SM, semimembranosus.
distribution across all muscles, and analyses were therefore performed on the nontransformed data to aid interpretation. T2 times were significantly increased after exercise in all muscles in each leg, except for the AM in both legs (Table 1). Post hoc tests showed that T2 changes in the uninjured leg were significantly larger for the BFlh versus AM (15.5 ± 4.3 percentage points, \( P = 0.004 \)), ST versus BFlh (10.3 ± 2.9 percentage points, \( P = 0.005 \)), ST versus BFsh (16.9 ± 3.2 percentage points, \( P < 0.0001 \)), ST versus SM (16.9 ± 2.9 percentage points, \( P < 0.0001 \)), and ST versus AM (25.8 ± 4.2 percentage points, \( P < 0.0001 \)) (Fig. 2). For the previously injured leg, post hoc tests showed a significantly higher activation for the ST versus BFlh (22.3 ± 2.8 percentage points, \( P < 0.0001 \)), ST versus BFsh (26.3 ± 3.2 percentage points, \( P < 0.0001 \)), ST versus SM (29.4 ± 3.9 percentage points, \( P < 0.0001 \)) (Fig. 2). Removal of outliers did not substantially alter these findings, with only the magnitude of the effects differing slightly.

### Between-leg differences in muscle activation

The mixed model indicated significantly lower BFlh activation in the injured compared with the uninjured leg, with no significant differences for the other muscles (Table 1, Fig. 3). These findings were robust to removal of outliers. There were no significant correlations between the difference in BFlh and ST or SM activation (\( r = -0.12, P = 0.71 \), and \( r = 0.17, P = 0.60 \), respectively). There was also no significant correlation between the time since injury and the difference in BFlh muscle activation between legs (\( r = 0.34, P = 0.28 \)) or between rehab time and the difference in BFlh muscle activation between legs (\( r = 0.04, P = 0.91 \)).

### Between-leg difference in muscle CSA

Muscle CSA did not significantly differ between the legs for any of the investigated muscles (Table 2, Fig. 3).

### Reliability

The between-rater reliability of muscle CSA was excellent, with ICCs of 0.94 (95% CI, 0.92–0.96) for BFlh, 0.95 (95% CI, 0.93–0.96) for BFsh, 0.98 (95% CI, 0.98–0.99) for ST, and 0.93 (95% CI, 0.90–0.94) for SM; the between-rater SEs of measurement were 1.32, 0.70, 1.04, and 1.59 cm², respectively.

### DISCUSSION

Our primary aim was to compare BFlh muscle activation as measured by exercise-induced T2 shifts between the injured and uninjured legs of a participant during the SLRCH exercise. In support of our hypothesis, we show significantly lower BFlh activation in the previously injured leg. Notably, BFlh muscle CSA was not significantly different between the legs. Our hypothesis related to equal activation of the medial and lateral hamstrings in the uninjured leg (our secondary aim).
Table 2

<table>
<thead>
<tr>
<th>Muscle Cross-Sectional Area (cm²) and Difference between Legs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle</td>
</tr>
<tr>
<td>BF₁₉</td>
</tr>
<tr>
<td>BF₉</td>
</tr>
<tr>
<td>ST</td>
</tr>
<tr>
<td>SM</td>
</tr>
<tr>
<td>AM</td>
</tr>
</tbody>
</table>

AM, adductor magnus; BF₁₉, biceps femoris long head; BF₉, biceps femoris short head; CI, confidence interval; NA, not available; SD, standard deviation; SE, standard error; SM, semimembranosus; ST, semitendinosus.
findings suggest that cortical inhibitory inputs to the motor cortex may contribute to the observed inhibition (2,3), which is likely caused by pain and swelling during the initial stages of injury and ultimately leads to inhibition in the absence of pain (3). Furthermore, some findings indicate that there is a difference between pushing and holding isometric muscle actions, with the latter being more similar to eccentric muscle actions in terms of muscle activation (10).

Because inhibition is mostly present during eccentric actions, this mechanism may additionally explain the presence of inhibition for the BF_{th} in our study. Moreover, studies that observed hamstring inhibition typically showed this when assessing at longer muscle-tendon unit lengths (6,31). Because the SLRCH is performed at a moderate to long muscle tendon unit length (27), this could further contribute to the observed inhibition.

In the uninjured leg, all muscles except for the AM showed a significant increase in T_{2} time. This finding adds to a growing body of literature demonstrating the usefulness of the SLRCH exercise as an effective training stimulus for the hamstring muscles (11,27). However, not all hamstring muscles were activated to a similar extent. Specifically, T_{2} times were longer for the ST compared with all other muscles, thus demonstrating an overall bias toward high ST activation. This observation is in line with previous research on the supine hamstring bridge, where ST activation was also higher than BF_{th} activation (Cohen’s d = 0.9), although the difference was not significant (22). The higher ST activation compared with SM and BF_{th} activation may partly reflect its role in preventing anterior tibial translation (22). No significant differences were observed between the SM and BF_{th}. Approximately equal activation of the SM and BF_{th} has also previously been observed during the single-leg supine bridge using similar methodology (22,26), and is in line with approximately equal activation of these muscles during the SLRCH as determined by musculoskeletal modeling (27).

We found no significant differences in BF_{th} muscle CSA between the legs, suggesting the inhibition observed for the BF_{th} did not result in substantial and consistent atrophy across participants. Similarly, the trend toward higher ST activation did not result in a significantly larger ST CSA. This observation is in agreement with some but not all previous studies (5,32,33). Differences in rehabilitation protocols between studies and differences in CSA assessment (e.g., CSA vs volume) could explain these differences. In addition, it is possible that inhibition may particularly impact muscle architectural adaptations, such as fascicle length (34), rather than CSA by limiting activation at longer muscle lengths and during eccentric actions, thereby reducing fascicle length adaptations (27). Indeed, a relatively short BF_{th} fascicle length has been shown to be a risk factor for hamstring injuries and to be shorter in a previously injured BF_{th}, with authors suggesting this to be a potential consequence of inhibition during the rehabilitation process (34,35).

Nevertheless, muscles that showed decreased activation typically showed a trend toward smaller CSA (Fig. 3), whereas muscles with higher activation showed a trend toward larger CSA. This suggests that the observed differences in activation have small effects on adaptations in CSA, but that our sample size might have been too small to detect such relations.

**Limitations**

There are several limitations to this study that should be considered when interpreting the findings. First, our cross-sectional design precludes the possibility of considering alterations in muscle activation as consequences or causes of hamstring injuries. Similarly, muscle activation could be altered in the uninjured leg, which could have affected these findings. However, other studies have shown similar results in MRI-derived muscle activation between the uninjured leg of injured individuals and completely injury-free individuals (5), suggesting our findings in the uninjured leg are likely generalizable to uninjured individuals. Second, there was a wide range in time between the injury and MRI assessment (150–330 days) between individuals. However, similar to previous studies (5), we did not observe a significant relation between the time since injury and the difference in BF_{th} muscle activation between legs (r = 0.34, P = 0.28) or rehab time and the difference in BF_{th} muscle activation between legs (r = 0.04, P = 0.91), suggesting the range of times did not impact our findings. Third, changes in T_{2} time do not reflect muscle force production per se, but rather reflect the metabolic response of muscles. The metabolic response is influenced by numerous factors, such as the capillary density and oxidative enzyme concentration (36), which could explain some of the variability in the observed T_{2} times between individuals (Fig. 2). We attempted to minimize this effect by recruiting a relatively homogeneous group of recreationally active soccer players and sprint athletes with a limited age range and by ensuring all participants performed the exercise with the same relative load as determined by the repetition maximum test. Nevertheless, strong correlations (r = 0.87) have been observed between T_{2} time and the force generated by a muscle during exercise (23). Similarly, changes in T_{2} time have been shown to correlate very strongly (r = 0.99) with sEMG measurements during exercise (14), thus demonstrating the usefulness of this method for inferring muscle activation despite the potential influence of factors such as capillary density. Another factor that could have contributed to the variability in T_{2} time within each muscle between individuals is that we did not strictly control internal or external hip rotation, which may preferentially activate either the medial or lateral hamstrings (37). A fourth limitation is that while our approach can be used to infer differences in muscle activation between muscles, it does not provide information on the activation relative to the maximum activation. Previous research has shown that the hamstrings are activated up to ~50% of the maximum during the SLRCH as determined by sEMG (27). Such activation magnitudes were comparable to other hamstring exercises, such as the Nordic hamstring exercise, suggesting the observed activation magnitudes likely have physiological relevance. A final limitation is that our sample consisted solely of males, despite attempts to recruit females for multiple months. However, previous research has shown that muscle activation patterns observed in males are similar in females (38).

**Implications**

The findings of this study have potential implications. First, in line with previous studies investigating hamstring exercises, we observed preferential activation of the ST over the BF_{th} in the uninjured leg (5,19,20). However, the magnitude of this effect (~10 percentage-point difference in activation) is smaller than in other studies (e.g., 17–30 percentage-point difference in the Nordic hamstring curl [5,19]). Second, BF_{th} activation was significantly lower (~7.1%) in the previously injured leg. This reduction is very much in line with the previously observed 7.9% reduction in BF_{th} T_{2} activation during the Nordic hamstring exercise (5). These findings collectively suggest that implementation of an isometric position-control exercise such as the SLRCH may allow for more specific targeting of the BF_{th} than other hamstring exercises in uninjured individuals but does not allow training of the BF_{th} with less inhibition in injured individuals. Future studies could explore if
real-time feedback on muscle activation during rehabilitation (e.g., using sEMG) may aid in relearning to recruit the BFm.

**Conclusion**

Our findings show that the ST is preferentially activated during the SLRCR in both the previously injured and uninjured legs. However, the magnitude of preferential activation in the uninjured leg is lower than previously reported in eccentric exercises. Furthermore, the BFm in the previously injured leg was activated less compared with the BFm in the uninjured leg, despite no differences in muscle CSA.

**REFERENCES**


