Title:

A novel apparatus measuring knee flexor strength during various hamstring exercises: A reliability and retrospective study

Authors:

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Abstract

Study Design: Reliability and case-control injury study.

Objectives: To establish test re-test reliability of a novel apparatus measuring knee flexor strength during various hamstring exercises; to investigate whether these measures detect between-leg differences in males with and without history of unilateral hamstring strain injury (HSI).

Background: Knee flexor strength is a key variable when dealing with HSI and methodologies of objective measurement are often limited to single exercises.

Methods: Twenty males without and ten males with previous unilateral HSI participated. Isometric knee flexor strength and peak rate of force development (RFD) at 0/0, 45/45 and 90/90 degrees of hip/knee flexion were measured, as well as force impulse during bilateral and unilateral variations of an eccentric slider and hamstring bridge, using a novel apparatus. Intraclass correlation coefficient (ICC), typical error (TE) and typical error as a co-efficient of variation (%TE) were calculated for all measures. The magnitude of between-leg differences within each group were calculated using estimates of effect sizes reported as Cohen's *d* with a ± 90% confidence interval (CI).

Results: Moderate to high test re-test reliability was observed for isometric knee flexor strength (ICC = 0.87 to 0.92) and peak RFD (ICC = 0.87 to 0.95) across three positions and mean force impulse during the eccentric slider (ICC = 0.83 to 0.90). In those with prior HSI, large deficits were seen in the previously injured leg compared to the contralateral uninjured leg for mean force impulse during the unilateral eccentric slider (*d* = -1.09, 90% CI = -0.20 to -1.97), isometric strength at 0/0 (*d* = -1.06, 90% CI = -0.18 to -1.93) and 45/45 (*d* = -0.88, 90% CI = -0.02 to -1.74) and peak RFD at 45/45 (*d* = -0.88, 90% CI = -0.02 to -1.74).

Conclusions: The novel apparatus provides a reliable measure of isometric knee flexor strength, peak RFD and force impulse during an eccentric slider, with deficits seen in previously injured hamstrings for these measures.

Keywords: Muscle; strain injury; isometric; rate of force development; eccentric, force impulse

Introduction

For researchers and clinicians, knee flexor strength is a variable of interest when dealing with hamstring strain injuries (HSI), a persistent issue in a range of sports [5, 6, 19] with associated financial consequences.[7] Risk of HSI increases with lower eccentric knee flexor strength [18, 25] and greater between-leg differences in isometric knee flexor strength may indicate re-injury risk and the time-course of recovery during rehabilitation.[1, 4, 12] Despite such evidence, objective knee flexor strength measures are scarcely implemented as part of return to play criteria following HSI,[8] potentially contributing to persistent deficits seen in previously injured hamstrings.[16, 26]

Isokinetic dynamometry is a methodology which has been implemented as part of HSI return to play decision making [8] and provides a reliable objective measure of knee flexor strength.[21] However, the clinical utility of isokinetic dynamometry is often limited to a laboratory environment due to high cost and technical requirements. As a clinically-practical alternative, handheld dynamometry can be used to measure isometric and eccentric knee flexor strength, although its reliability is dependent on clinician strength and skill.[3, 29] To overcome clinician dependency, several studies have implemented externally fixed dynamometry to provide an objective measure of knee flexor strength which may still be clinically practical.[1, 10, 15, 24, 30]

To date, reports of externally fixed dynamometry tend to measure isometric knee flexor strength at a single position and have not investigated variables such as rate of force development (RFD), also shown to be deficient in previously injured hamstrings.[17]

Externally fixed dynamometry is mostly used to measure knee flexor strength during isometric tests, although quantifying force output during dynamic exercises may have additional benefits. Being able to quantify force output during dynamic hamstring exercises may improve the clinician's ability to make more objective decisions around the progression of HSI rehabilitation, a process that is typically subjective.[8] Identifying methods of quantifying force output during both bilateral and unilateral hamstring exercises, which could be employed during HSI rehabilitation, is likely of interest to clinicians.

Therefore, the purpose of this study was to establish test-retest reliability of a novel apparatus measuring isometric knee flexor strength and RFD at three hip and knee joint angles as well as left and right leg force outputs independently during bilateral and unilateral variations of an eccentric slider and hamstring bridge. Further to this, the study also aims to determine whether these measures detect between-leg differences in males with and without history of unilateral HSI.

Methods

Twenty males with no history of HSI formed the control group and ten males with a history of at least one unilateral HSI within the past 18 months formed the previous HSI group. Participants in both groups were recreationally active, participating in physical activity twice per week as a minimum. Following ethical approval granted by the Australian Catholic

University Human Research Committee (2015-253H), all participants provided written informed consent prior to commencing testing. Injury history was obtained during a subjective interview conducted by a health professional (JH) with four year's clinical experience in musculoskeletal injury assessment and rehabilitation. Previous HSI was defined as acute onset posterior thigh pain resulting from a typical mechanism of HSI (i.e. high speed running, acceleration, deceleration, etc.), causing immediate cessation of activity and at least seven days absence from regular activity participation.[22] At the time of testing, all participants with a prior HSI had subsequently returned to their normal level of activity and both groups were free from any current lower limb or lumbo-pelvic pain or injury.

Participants in the control group attended the Australian Catholic University research laboratory on three occasions, whilst the previous HSI group attended on two occasions. Each visit was separated by seven days and lasted approximately 45 to 60 minutes. All visits consisted of isometric knee flexor contractions at three different hip/knee joint angles (0/0, 45/45 and 90/90 degrees), as well as bilateral and unilateral variations of the eccentric slider and hamstring bridge exercises. All of these measures were performed in a novel apparatus consisting of two adjustable ratchet straps hanging in parallel from a power cage, with a wired load cell (MLP-750, Transducer Techniques, Temecula CA, USA) and heel strap attached in series with each (figure 1). All load cell data was sampled at 2000Hz and transferred to a laptop computer via an analogue input data acquisition card (NI9237, National Instruments, Austin TX, USA) and monitored via a custom written software visual interface (LabVIEW 2013 National Instruments, Austin TX, USA). Offline analysis of all data was later performed using custom written code in R [23] version 3.2.4.

Isometric knee flexor contractions were performed at 0/0, 45/45 and 90/90 degrees of hip/knee flexion while participants were supine on a plinth placed at the end of the apparatus, with an additional strap used to secure participant's pelvis to the plinth (figure 2). In each position participants performed two submaximal repetitions at 50% and then 75% of perceived maximum, followed by three maximal repetitions of three to five seconds duration, with a minimum 30 seconds rest between each. Standardised instructions were given to "push your heel down into the strap, without countermovement, as fast and hard as you can, in three, two, one, go" with strong verbal encouragement provided to ensure maximal effort. Testing position and leg order was randomised for each participant during their first visit, with this order maintained for subsequent sessions and for unilateral variations of the eccentric slider and hamstring bridge.

Data for all isometric knee flexor contractions were corrected for leg weight, calculated as the resting force output collected prior to each repetition. Isometric knee flexor strength was defined as the highest recorded force output across the three repetitions for each leg, at each of the three testing positions. In addition to this, peak RFD defined as the greatest increase in force over a rolling 200ms window, from contraction onset (increase in resting force ≥ 4N), until the time point where peak force was achieved. Peak RFD over a 200ms window was selected as this has previously been shown to be more reliable than alternative methodologies.[11, 13] In order to identify contraction onset, the data was low pass filtered (10Hz) using a zero-lag fourth order Butterworth filter. To reduce the chance of countermovement influencing RFD, [11] repetitions with a decrease in resting force ≥ 4N in the 200ms prior to contraction onset were removed from analysis. Identification and removal of repetitions with a countermovement was done in a systematic fashion using custom written code in R [23] to reduce risk of subjective bias. Of the remaining repetitions, the single repetition with the greatest peak RFD (N/s) for each leg in each position was used for later analysis.

Prior to commencing the eccentric slider and hamstring bridge, leg weight was calculated as the resting force output of each leg independently, with participants laying supine on the plinth, arms across their chest and heels resting in the straps of the apparatus, ensuring 0/0 degrees of hip/knee flexion (figure 3a). From the position used to ascertain resting leg weight, participants got into the starting position for the eccentric slider by flexing their knees (figure 3b), then lifting their hips up from the plinth creating a straight line from shoulders to knees (figure 3c).

For the bilateral variation, on the “go” command, participants extended both knees as slowly as possible using their knee flexors to control the movement, keeping hips elevated (figure 3d-f; ONLINE VIDEO). The unilateral variation was performed in the same way, except on the “go” command, participants lifted the contralateral leg so that active force was only being applied through the heel of the leg being assessed (figure 3g-i; ONLINE VIDEO). A repetition was deemed complete when full knee extension was reached or when hip extension could not be maintained. Three repetitions of the bilateral and unilateral eccentric slider on each leg were performed by all participants following practice repetitions. The tester (JH) had to be satisfied with technique prior to allowing participants to progress to test repetitions.

The bilateral hamstring bridge was performed from 45/45 degrees of hip/knee flexion, with participants lifting their hips from the plinth until they achieved a straight line from their shoulders to knees, before returning to the starting position (figure 4a-c; ONLINE VIDEO). The unilateral variation was performed in the same way except that the leg not being assessed was held out of the strap at approximately 90/90 degrees of hip/knee flexion (figure 4d-f; ONLINE VIDEO). Speed of each repetition was controlled by a metronome to ensure approximately a three second up (concentric) and three second down (eccentric) phase. Three repetitions of the bilateral and unilateral hamstring bridge on each leg were performed by all participants following practice repetitions. The tester (JH) had to be satisfied with technique prior to allowing participants to progress to test repetitions.

Following correction for resting leg weight, area under the force time curve from the start to end of each eccentric slider and hamstring bridge repetition was defined as force impulse normalised to each participant’s body mass (N.s/kg). The start of a bilateral eccentric slider repetition was defined as the first collected data point which coincided with the “go” command, whereas the start of a unilateral eccentric slider repetition was the point at which force of the contralateral leg dropped below resting leg weight. The start of a hamstring bridge repetition was calculated as the point which force exceeded resting leg weight for the bilateral variation or 2 x resting leg weight for the unilateral variation. The end of a repetition for both the eccentric slider and hamstring bridge was calculated as the point which force dropped below resting leg weight for each leg independently for the bilateral variation and 2 x resting leg weight for the unilateral variation. Force impulse was calculated for each repetition with the average of the three repetitions performed for each exercise variation (termed mean force impulse), used for later analysis. It is important to note that the measure of mean force impulse involved the combination of the concentric and eccentric phases for the hamstring bridge, whereas for the eccentric slider, only the eccentric phase was used for data analysis.

To determine test re-test reliability, descriptive statistics for all measures from the dominant and non-dominant legs of the control group across three visits were screened for normal distribution, using the Shapiro-Wilk test in SPSS Version 23.0.0.3 (IBM Corporation, Chicago, IL). Intraclass correlation coefficient (ICC), typical error (TE) and typical error as a co-efficient of variation (%TE) were calculated using a custom spreadsheet, with log-transformed data reported for non-normally distributed measures.[9] Based on previous studies of similar test re-test reliability data, [15, 26] an ICC ≥ 0.90 was considered to be high, between 0.80 and 0.89 moderate and ≤ 0.79 poor. Minimum detectable change at a 95% confidence interval (MDC_{95}) was calculated as TE x 1.96 x $\sqrt{2}$.

Within each group, between-leg comparisons were performed using data from the second visit, to account for an anticipated learning effect from visits one to two. The magnitude of between-leg differences were calculated using estimates of effect sizes reported as Cohen's *d* with a ± 90% confidence interval (CI) using the "effsize" package [27] in R.[23] Cohen's *d* of ≥0.8, ≥0.5, ≥0.2 and <0.2 were respectively considered large, moderate, small and trivial, whilst any effects where the 90% CI overlapped both the positive (>0.2) and negative (<-0.2) thresholds of a small effect simultaneously, were defined as unclear.[2] To provide a relative comparison of between-leg differences across all measures, asymmetry was calculated as the non-dominant leg divided by the dominant leg in the control group and the previously injured leg divided by the uninjured leg in the previous HSI group and expressed as a percentage. In the control group, leg dominance was determined by asking participants which leg they prefer to kick a ball with. Due to recently discussed limitations in the selective reporting of p-values,[28] these were not calculated as part of primary statistical analysis but can be found in supplementary material.

Results

For clarity, all data are reported as mean±standard deviation unless otherwise stated. Participants' age, stature and mass were 24±4 years, 178±7cm, 79±10kg in the control group and 24±4 years, 182±8cm, 86±9kg in the previous HSI group. Median time from most recent HSI was 9 months, ranging from 1 to 15 months.

Test re-test reliability ranged from moderate to high for isometric strength (ICC = 0.87 to 0.92; TE% = 6.2 to 8.1) and peak RFD (ICC = 0.87 to 0.95; TE% = 9.9 to 12.4) across the three positions assessed and for mean force impulse during the unilateral eccentric slider (ICC = 0.87 to 0.90; TE% = 16.4 to 17.4). Mean force impulse during the bilateral eccentric slider was moderately reliable (ICC = 0.83 to 0.87; TE% = 20.2 to 21.2) and ranged from poor to high during the unilateral (ICC = 0.78 to 0.92; TE% = 4.8 to 7.1) and bilateral (ICC = 0.57 to 0.81, TE% = 8.5 to 13.8) variations of the hamstring bridge. All test re-test reliability data can be found in Table 1.

Among participants with prior HSI, large deficits were seen in the previously injured leg compared to contralateral uninjured leg for mean force impulse during the unilateral eccentric slider (d = -1.09, 90% CI = -0.20 to -1.97), isometric strength at 0/0 (d = -1.06, 90% CI = -0.18 to -1.93) and 45/45 (d = -0.88, 90% CI = -0.02 to -1.74), as well as peak RFD at 45/45 (d = -0.88, 90% CI = -0.02 to -1.74). Moderate deficits were seen in the previously injured leg compared to the contralateral uninjured leg for peak RFD at 0/0 (d = -0.75, 90%CI = 0.10 to -1.59), isometric strength at 90/90 (d = -0.69, 90%CI = 0.15 to -1.54) and mean force impulse during the bilateral bridge (d = -0.65, 90%CI = 0.19 to -1.49). In the control group, a small effect of leg dominance at 0/0 was seen for peak RFD (d = -0.48, 90%CI = 0.07 to -

1.04) and isometric strength (*d* = -0.40, 90%CI = 0.15 to -0.96). All other between-leg differences were unclear (supplementary table), with a summary of between-leg asymmetry in percentage terms for all measures shown in Figure 5.

Discussion

The main findings of the current study are that i) the novel apparatus was moderately to highly reliable when measuring isometric knee flexor strength and peak RFD across three positions, as was mean force impulse during an eccentric slider; and ii) individuals with prior HSI display large deficits in the previously injured leg compared to their contralateral uninjured leg for isometric knee flexor strength, peak RFD and mean force impulse during a unilateral eccentric slider.

When measuring isometric knee flexor strength, test re-test reliability of the current apparatus is comparable to previous investigations implementing externally fixed dynamometry [1, 30] with the advantage of employing a range of hip/knee joint angles. In contrast to other retrospective investigations reporting an absence of between-leg deficits in isometric knee flexor strength, [20, 26] moderate to large deficits were seen in the previous HSI group. Such findings may be partly explained by the range of hip/knee joint angles employed in the current study, which allowed for assessment of isometric knee flexor strength at longer hamstring muscle lengths involving hip flexion, compared to a prone position with no hip flexion.[20, 26]

The supine testing position also enabled analysis of isometric RFD, as the force output could be detected from a position of complete rest, allowing more accurate identification of contraction onset and countermovement.[11] Peak RFD over a 200ms window was analysed, as this requires simpler offline analysis and is more reliable than other RFD analysis methodologies,[11, 13] improving potential for future clinical implementation with automated analysis. It is unclear from the current findings whether peak RFD provides any clinically useful information additional to isometric knee flexor strength, as peak RFD deficits found in previously injured hamstrings were of a similar or lesser magnitude to deficits in isometric strength. Nevertheless, given the moderate to high reliability of peak RFD, implementation of the current apparatus in future studies may be warranted in populations where knee flexor RFD may be of interest, such as those with acute HSI[17] or anterior cruciate ligament injury.[14]

In addition to isometric strength and RFD, the current study reports for the first time, the measure of force impulse of the left and right legs independently during two exercises, the eccentric slider and hamstring bridge. Whilst independent knee flexor force output of the left and right legs have previously been objectively measured during the bilateral Nordic hamstring exercise (NHE), [15] the current apparatus allows objective measurement of force output during both bilateral and unilateral exercises. Another key difference between the NHE and the exercises employed in the current study is that the eccentric slider and hamstring bridge are submaximal in nature, which may have application for clinicians. For example, monitoring force impulse during the submaximal bilateral eccentric slider may provide an objective guide for progression to maximal eccentric knee flexor exercises during HSI rehabilitation such as the NHE. Furthermore, instantaneous force output can be displayed, providing the clinician and patient visual feedback on between-leg contributions when performing the eccentric slider and hamstring bridge during HSI rehabilitation.

The major difference between the two exercises employed in the current study was that the eccentric slider only assessed the eccentric phase which was performed as slowly as possible, whereas the hamstring bridge involved both a concentric and eccentric phase with repetition speed controlled. As such, TE% of mean force impulse during the eccentric slider was higher compared to the hamstring bridge, but allowed for greater differentiation between previously injured and uninjured hamstrings, reflected in the relatively higher ICCs. Therefore, caution should be taken when interpreting subtle between-leg differences in mean force impulse during the eccentric slider, although large between-leg deficits such as those seen in the previous HSI group during the unilateral variation may still be detected.

The novel apparatus used in this study utilised commercially available equipment that is relatively inexpensive (cost < $1000USD) and is not confined to a laboratory setting unlike isokinetic or externally fixed dynamometry. It is acknowledged that the methods of data analysis employed in the current study require some technical expertise, however, ongoing development of custom written code using free and open source R software [23] will allow for simpler automated analysis, improving potential for clinical utility.

The current study has some limitations. Firstly, the study included recreationally active participants who performed a minimum of two days of physical activity per week, however the type, volume and/or intensity of exercise beyond these minimum requirements was not controlled for. Secondly, retrospective injury history and details of rehabilitation were restricted to subjective reporting. As a result, the severity of previous HSI and exposure to stimulus for adaptation are unknown, with both of these factors likely to influence subsequent knee flexor strength and function. Thirdly, as with any retrospective investigation, it is also unknown whether the between-leg deficits seen in the previous HSI group were a result or cause of initial injury. Fourthly, it is acknowledged that muscles such as gastrocnemius and gracilis also contribute to knee flexor force output in addition to the hamstrings, whilst the contribution of the hip extensors during the hamstring bridge and eccentric slider cannot be directly quantified. Finally, measures of knee flexor strength in the current study were not compared to gold standard tools such as isokinetic dynamometry.

Conclusion

The novel apparatus is capable of objectively measuring both isometric knee flexor strength and peak RFD across a range of hip/knee joint angles, as well as force impulse during an eccentric slider, with moderate to high reliability. Large between-leg deficits were observed in previously injured hamstrings for isometric knee flexor strength, peak RFD and mean force impulse during the unilateral eccentric slider when using the apparatus. It is hoped that future implementation of such an apparatus will improve the ability of both clinicians and researchers to objectively monitor knee flexor strength in clinical populations of interest such as those with a HSI and improve rehabilitation outcomes.

Key Points

Findings: The novel apparatus is moderately to highly reliable when measuring isometric knee flexor strength, peak RFD and mean force impulse during an eccentric slider with large between-leg deficits seen in previously injured hamstring for these measures.

Implications: Clinicians and researchers may implement such a novel apparatus to monitor knee flexor strength during HSI rehabilitation and improve their ability to make clinical decisions based on objective data.

Caution: The small sample size and recreationally active status of the previous HSI group limits interpretation of the retrospective between-leg deficits seen in the current study. The retrospective nature of these between-leg comparisons also does not inform whether deficits in previously injured hamstrings were a result or cause of initial HSI.

References

1. Askling C, Saartok T, Thorstensson A. Type of acute hamstring strain affects flexibility, strength, and time to return to pre-injury level. *Br J Sports Med.* 2006;40(1):40-4. doi:10.1136/bjsm.2005.018879.

2. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform.* 2006;1(1):50-7.

3. Bohannon RW. Test-retest reliability of hand-held dynamometry during a single session of strength assessment. *Phys Ther.* 1986;66(2):206-9.

4. De Vos RJ, Reurink G, Goudswaard GJ, Moen MH, Weir A, Tol JL. Clinical findings just after return to play predict hamstring re-injury, but baseline mri findings do not. *Br J Sports Med.* 2014;48(18):1377-84. doi:10.1136/bjsports-2014-093737.

5. Ekstrand J, Hagglund M, Walden M. Injury incidence and injury patterns in professional football: The UEFA injury study. *Br J Sports Med.* 2011;45(7):553-8. doi:10.1136/bjsm.2009.060582.

6. Elliott MC, Zarins B, Powell JW, Kenyon CD. Hamstring muscle strains in professional football players: A 10-year review. *Am J Sports Med.* 2011;39(4):843-50. doi:10.1177/0363546510394647.

7. Hickey J, Shield AJ, Williams MD, Opar DA. The financial cost of hamstring strain injuries in the Australian Football League. *Br J Sports Med.* 2014;48(8):729-30. doi:10.1136/bjsports-2013-092884.

8. Hickey JT, Timmins RG, Maniar N, Williams MD, Opar DA. Criteria for progressing rehabilitation and determining return-to-play clearance following hamstring strain injury: A systematic review. *Sports Med.* 2016. doi:10.1007/s40279-016-0667-x. [Epub ahead of print].

9. Hopkins WG. Spreadsheets for analysis of validity and reliability. *Sportscience.* 2015;19:36-42.

10. Kollock RO, Jr., Onate JA, Van Lunen B. The reliability of portable fixed dynamometry during hip and knee strength assessments. *J Athl Train.* 2010;45(4):349-56. doi:10.4085/1062-6050-45.4.349.

11. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J. Rate of force development: Physiological and methodological considerations. *Eur J Appl Physiol.* 2016;116(6):1091-116. doi:10.1007/s00421-016-3346-6.

12. Maniar N, Shield AJ, Williams MD, Timmins RG, Opar DA. Hamstring strength and flexibility after hamstring strain injury: A systematic review and meta-analysis. *Br J Sports Med.* 2016. doi:10.1136/bjsports-2015-095311.

13. Mentiplay BF, Perraton LG, Bower KJ et al. Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: A reliability and validity study. *PLoS One.* 2015;10(10). doi:ARTN e0140822
10.1371/journal.pone.0140822.

14. Mirkov DM, Knezevic OM, Maffiuletti NA, Kadija M, Nedeljkovic A, Jaric S. Contralateral limb deficit after ACL-reconstruction: An analysis of early and late phase of rate of force development. *J Sports Sci.* 2017;35(5):435-40. doi:10.1080/02640414.2016.1168933.

15. Opar DA, Piatkowski T, Williams MD, Shield AJ. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: A reliability and retrospective injury study. *J Orthop Sports Phys Ther.* 2013;43(9):636-40. doi:10.2519/jospt.2013.4837.

16. Opar DA, Williams MD, Timmins RG, Dear NM, Shield AJ. Knee flexor strength and bicep femoris electromyographical activity is lower in previously strained hamstrings. *J Electromyogr Kinesiol.* 2013;23(3):696-703. doi:10.1016/j.jelekin.2012.11.004.

17. Opar DA, Williams MD, Timmins RG, Dear NM, Shield AJ. Rate of torque and electromyographic development during anticipated eccentric contraction is lower in previously strained hamstrings. *Am J Sports Med.* 2013;41(1):116-25. doi:10.1177/0363546512462809.

18. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ, Shield AJ. Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Med Sci Sports Exerc.* 2014. doi:10.1249/MSS.0000000000000465.

19. Orchard JW, Seward H, Orchard JJ. Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *Am J Sports Med.* 2013;41(4):734-41. doi:10.1177/0363546513476270.

20. Reurink G, Goudswaard GJ, Moen MH et al. Rationale, secondary outcome scores and 1-year follow-up of a randomised trial of platelet-rich plasma injections in acute hamstring muscle injury: The Dutch hamstring injection therapy study. *Br J Sports Med.* 2015. doi:10.1136/bjsports-2014-094250.

21. Sole G, Hamren J, Milosavljevic S, Nicholson H, Sullivan SJ. Test-retest reliability of isokinetic knee extension and flexion. *Arch Phys Med Rehabil.* 2007;88(5):626-31. doi:10.1016/j.apmr.2007.02.006.

22. Sole G, Milosavljevic S, Nicholson HD, Sullivan SJ. Selective strength loss and decreased muscle activity in hamstring injury. *J Orthop Sports Phys Ther.* 2011;41(5):354-63. doi:10.2519/jospt.2011.3268.

23. Team RC. R: A language and environment for statistical computing. Vienna, Austria: R foundation for statistical computing; 2016.

24. Thorborg K, Bandholm T, Holmich P. Hip- and knee-strength assessments using a hand-held dynamometer with external belt-fixation are inter-tester reliable. *Knee Surg Sports Traumatol Arthrosc.* 2013;21(3):550-5. doi:10.1007/s00167-012-2115-2.

25. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): A prospective cohort study. *Br J Sports Med.* 2015. doi:10.1136/bjsports-2015-095362.

26. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Biceps femoris long head architecture: A reliability and retrospective injury study. *Med Sci Sports Exerc.* 2015;47(5):905-13. doi:10.1249/MSS.0000000000000507.

27. Torchiano M. Effsize: Efficient effect size computation. 2016.

28. Wasserstein RL, Lazar NA. The ASA's statement on p-values: Context, process, and purpose. *Am Stat.* 2016;70(2):129-31. doi:10.1080/00031305.2016.1154108.

29. Whiteley R, Jacobsen P, Prior S, Skazalski C, Otten R, Johnson A. Correlation of isokinetic and novel hand-held dynamometry measures of knee flexion and extension strength testing. *J Sci Med Sport.* 2012;15(5):444-50. doi:10.1016/j.jsams.2012.01.003.

30. Wollin M, Purdam C, Drew MK. Reliability of externally fixed dynamometry hamstring strength testing in elite youth football players. *J Sci Med Sport.* 2015. doi:10.1016/j.jsams.2015.01.012.

TABLE 1. Test re-test reliability of the dominant and non-dominant legs in the control group.

Measure	Visit 1 (mean±SD)	Visit 2 (mean±SD)	Visit 3 (mean±SD)	ICC (95% CI)	TE (95% CI)	TE% (95% CI)	MDC_{95}
Isometric Strength (N)							
0/0 Dominant	249 ± 49	251 ± 48	243 ± 46	0.87 (0.74-0.94)	17.8 (14.3-24.1)	8.1 (6.5-11.2)	49.2
0/0 Non-dominant	239 ± 46	242 ± 41	235 ± 42	0.91 (0.81-0.96)	13.8 (11.1-18.8)	6.2 (5.0-8.6)	38.4
45/45 Dominant	337 ± 69	325 ± 61	332 ± 69	0.89 (0.77-0.95)	23.5 (18.9-31.9)	7.3 (5.8-10)	65.1
45/45 Non-dominant	328 ± 67	328 ± 61	327 ± 72	0.92 (0.82-0.96)	20.4 (16.4-27.7)	6.7 (5.4-9.2)	56.5
90/90 Dominant	346 ± 75	334 ± 69	340 ± 68	0.91 (0.81-0.96)	22.2 (17.8-30.1)	7.2 (5.8-9.9)	61.4
90/90 Non-dominant	341 ± 70	334 ± 67.5	336 ± 65	0.90 (0.79-0.96)	22.7 (18.3-30.9)	8.1 (6.5-11.2)	63.0
Isometric Peak RFD (N/s)							
0/0 Dominant	873 ± 235	873 ± 258	828 ± 236	0.90 (0.79-0.96)	82.0 (66.0-111.5)	10.6 (8.5-14.7)	227.4
0/0 Non-dominant	835 ± 240	818 ± 253	836 ± 225	0.90 (0.79-0.96)	81.2 (65.4-110.3)	12.2 (9.7-16.9)	225.0
45/45 Dominant	1113 ± 398	1057 ± 321	1102 ± 334	0.95 (0.89-0.98)	86.2 (69.4-117.2)	9.9 (7.9-13.7)	239.0
45/45 Non-dominant	1077 ± 358	1062 ± 327	1066 ± 361	0.92 (0.82-0.96)	107.3 (86.4-145.8)	12.4 (9.9-17.2)	297.4
90/90 Dominant	1202 ± 300	1205 ± 331	1214 ± 368	0.88 (0.75-0.95)	121.8 (96.8-165.0)	12.4 (9.7-17.1)	337.6
90/90 Non-dominant	1216 ± 332	1161 ± 354	1177 ± 366	0.92 (0.84-0.97)	102.4 (81.4-138.8)	11.6 (9.1-16.1)	284.0
Eccentric Slider Mean Force Impulse (N.s/kg)							
Bilateral Dominant	11.9 ± 6.6	14.0 ± 7.0	15.6 ± 7.9	0.87* (0.74-0.95)	2.7 (2.1-3.7)	20.2 (15.7-28.3)	7.5
Bilateral Non-dominant	12.1 ± 5.8	13.7 ± 6.0	15.4 ± 7.0	0.83* (0.66-0.93)	2.6 (2.1-3.6)	21.2 (16.5-29.8)	7.2
Unilateral Dominant	18.1 ± 9.7	22.7 ± 10.9	23.5 ± 11.0	0.87* (0.74-0.95)	3.2 (2.5-4.2)	17.4 (13.8-24.4)	8.9
Unilateral Non-dominant	19.2 ± 10.1	22.7 ± 11.7	23.4 ± 11.5	0.90* (0.79-0.96)	3.1 (2.5-4.2)	16.4 (13.0-22.9)	8.5
Hamstring Bridge Mean Force Impulse (N.s/kg)							
Bilateral Dominant	6.1 ± 1.2	6.7 ± 1.0	6.5 ± 1.0	0.57* (0.28-0.79)	0.7 (0.6-1.01)	13.8 (11.0-19.3)	2.0
Bilateral Non-dominant	6.7 ± 1.2	6.9 ± 1.4	6.7 ± 1.1	0.81* (0.62-0.91)	0.5 (0.4-0.7)	8.5 (6.8-11.7)	1.5
Unilateral Dominant	13.3 ± 1.9	13.9 ± 2.1	13.5 ± 1.9	0.78 (0.57-0.90)	1.0 (0.8-1.3)	7.1 (5.7-9.7)	2.7
Unilateral Non-dominant	13.9 ± 2.2	14 ± 2.1	13.9 ± 2.1	0.92 (0.84-0.97)	0.6 (0.5-0.8)	4.8 (3.9-6.6)	1.7

Abbreviations: ICC, intraclass correlation coeffiecient; MDC_{95}, minimal detectable change at 95% confidence level; TE, typical error; TE%, typical error as a coefficient of variation.

**Indicates ICC taken from log-transformed data due to non-normal distribution*

SUPPLEMENTARY TABLE. Between-leg asymmetry (%), effect sizes reported as Cohen's *d* with a ± 90% confidence interval (CI), raw and Holm's adjusted p-values obtained from paired t-tests for all between-leg comparisons within each group. Negative values indicate between-leg asymmetry/difference in favour of the dominant or contralateral uninjured leg in the control and previous HSI group respectively.

Measure	Asymmetry % (mean ± sd)	Cohen's *d* (90% CI)	Raw p value	Adjusted p value
Control (n = 20)				
Isometric Strength 0/0	-2.8 ± 9.2	-0.40 (0.15 to -0.96)	0.088	0.790
Isometric Strength 45/45	1.6 ± 12.2	0.05 (0.60 to -0.49)	0.809	1.000
Isometric Strength 90/90	0.6 ± 14.2	-0.02 (0.53 to -0.56)	0.937	1.000
Peak RFD 0/0	-5.7 ± 13.1	-0.48 (0.07 to -1.04)	0.045	0.446
Peak RFD 45/45	1.9 ± 14.9	0.04 (0.59 to -0.51)	0.857	1.000
Peak RFD 90/90	-3.3 ± 15.8	-0.24 (0.32 to -0.81)	0.305	1.000
Eccentric Slider Bilateral	1.6 ± 16.1	-0.13 (0.43 to -0.70)	0.573	1.000
Eccentric Slider Unilateral	0.3 ± 17.8	0.01 (0.56 to -0.53)	0.962	1.000
Hamstring Bridge Bilateral	4.4 ± 22.9	0.13 (0.67 to -0.42)	0.582	1.000
Hamstring Bridge Unilateral	1.9 ± 10.6	0.12 (0.67 to -0.42)	0.584	1.000
Previous HSI (n = 10)				
Isometric Strength 0/0	-10.8 ± 10.0	-1.06 (-0.18 to -1.93)	0.009	0.078
Isometric Strength 45/45	-12.5 ± 14.5	-0.88 (-0.02 to -1.74)	0.021	0.168
Isometric Strength 90/90	-8.6 ± 12.5	-0.69 (0.15 to -1.54)	0.056	0.279
Peak RFD 0/0	-9.2 ± 18.9	-0.75 (0.10 to -1.59)	0.043	0.256
Peak RFD 45/45	-14.5 ± 15.7	-0.88 (-0.02 to -1.74)	0.021	0.168
Peak RFD 90/90	-2.5 ± 22.1	-0.40 (0.42 to -1.23)	0.234	0.404
Eccentric Slider Bilateral	-13.8 ± 27.0	-0.64 (0.20 to -1.48)	0.074	0.279
Eccentric Slider Unilateral	-26.0 ± 20.7	-1.09 (-0.20 to -1.97)	0.007	0.075
Hamstring Bridge Bilateral	-11.0 ± 18.3	-0.65 (0.19 to -1.49)	0.069	0.279
Hamstring Bridge Unilateral	-2.9 ± 9.0	-0.44 (0.39 to -1.26)	0.202	0.404