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A Novel Apparatus to Measure Knee Flexor Strength During Various Hamstring Exercises: A Reliability and Retrospective Injury Study

SUPPLEMENTAL VIDEO ONLINE

For researchers and clinicians, knee flexor strength is a variable of interest when dealing with hamstring strain injury (HSI), which is a persistent issue in a range of sports[5,6,19] that has associated financial consequences.[7] Risk of HSI increases with lower eccentric knee flexor strength,[18,25] and, furthermore, greater between-leg differences in isometric knee flexor strength may indicate reinjury risk and longer recovery time 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 the persistent deficits seen in previously injured hamstrings.[16,26]

STUDY DESIGN: Reliability and case-control injury study.

BACKGROUND: Knee flexor strength is a key variable when dealing with hamstring strain injury (HSI), and methodologies of objective measurement of strength are often limited to single exercises.

OBJECTIVES: To establish test-retest reliability of a novel apparatus to measure knee flexor strength during various hamstring exercises, and to investigate whether the measure can detect between-leg differences in male participants with and without history of unilateral HSI.

METHODS: Twenty male participants without and 10 male participants with previous unilateral HSI participated. Isometric knee flexor strength and peak rate of force development (RFD) at 0°/0°, 45°/45°, and 90°/90° 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, and typical error as a coefficient of variation were calculated for all measures. The magnitudes of between-leg differences within each group were calculated using estimates of effect sizes, reported as Cohen's *d* and 90% confidence interval (CI).

RESULTS: Moderate to high test-retest reliability was observed for isometric knee flexor strength (ICC = 0.87-0.92) and peak RFD (ICC = 0.88-0.95) across 3 positions and for mean force impulse during the eccentric slider (ICC = 0.83-0.90). In those with prior HSI, large deficits were observed 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, –1.97), isometric strength at 0°/0° (*d* = –1.06; 90% CI: –0.18, –1.93) and 45°/45° (*d* = –0.88; 90% CI: –0.02, –1.74), and peak RFD at 45°/45° (*d* = –0.88; 90% CI: –0.02, –1.74).

CONCLUSION: 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. *J Orthop Sports Phys Ther 2018;48(2):72-80. Epub 26 Oct 2017. doi:10.2519/jospt.2018.7634*

KEY WORDS: *eccentric, force impulse, isometric, muscle, rate of force development, strain injury*

Isokinetic dynamometry, a methodology that has been implemented as part of HSI return-to-play decision making,[8] provides a reliable objective measure of knee flexor strength.[22] However, the clinical utility of isokinetic dynamometry is often limited to a laboratory environment due to its 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 that may still be clinically practical.[1,10,15,24,30] To date, reports of externally fixed dynamometry tend to measure isometric knee flexor

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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 about 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 to be of interest to clinicians.

Therefore, the purpose of this study was to establish test-retest reliability of a novel apparatus to measure isometric knee flexor strength and RFD at 3 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, the study also aimed to determine whether these measures detect between-leg differences in male participants with and without history of unilateral HSI.

METHODS

Twenty male participants with no history of HSI were included in the control group, and 10 male participants with a history of at least 1 unilateral HSI within the past 18 months were included in 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 (J.H.) with 4 years of 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 (ie, high-speed running, acceleration, deceleration, etc), causing immediate cessation of activity and at least 7 days' absence from regular activity participation.[23] At the time of testing, all participants with a prior HSI had returned to their normal level of activity, and both groups were free from any current lower-limb or lumbopelvic pain or injury.

Participants in the control group attended the Australian Catholic University research laboratory on 3 occasions, whereas the previous HSI group attended on 2 occasions. Each visit was separated by 7 days and lasted approximately 45 to 60 minutes. All visits consisted of isometric knee flexor contractions at 3 different hip/knee joint angles (0°/0°, 45°/45°, and 90°/90°), as well as bilateral and unilateral variations of the eccentric slider and hamstring bridge exercises. All of these measures were performed with a novel apparatus consisting of 2 adjustable ratchet straps hanging in parallel from a power cage, with a wired load cell (MLP-750; Transducer Techniques, LLC, Temecula, CA) and heel strap attached in series with each (**FIGURE 1**). All load cell data were sampled at 2000 Hz and transferred to a laptop computer via an analog input data-acquisition card (NI9237; National Instruments, Austin, TX) and monitored via a custom-written software visual interface (LabVIEW 2013; National Instruments). Offline analysis of all data was later performed using custom-written code in R Version 3.2.4.[20]

Isometric knee flexor contractions were performed at 0°/0°, 45°/45°, and 90°/90° 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 the participant's pelvis to the plinth (**FIGURE 2**). In each position, participants performed 2 submaximal repetitions at 50% and then 75% of perceived maximum, followed by 3 maximal repetitions of 3 to 5 seconds' duration, with a minimum 30-second rest between each. Standardized instructions were given to "push your heel down into the strap, without countermovement, as fast and hard as you can, in 3, 2, 1, go," with strong verbal encouragement provided to ensure maximal ef-

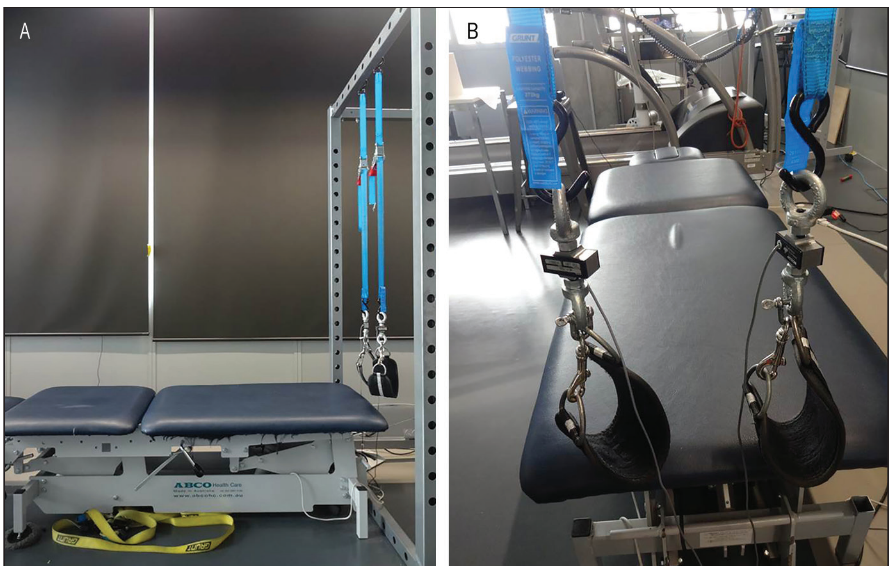

FIGURE 1. Novel apparatus consisting of 2 adjustable ratchet straps hanging in parallel from a power cage placed at the end of a plinth (A), with 2 independent load cells and ankle straps attached in series with each strap (B).

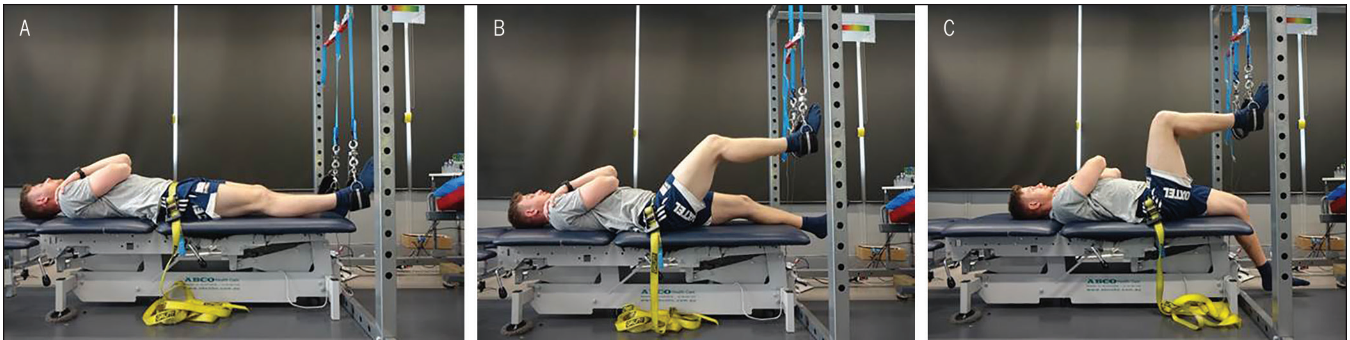

FIGURE 2. Positions used to perform isometric knee flexor contractions at 0°/0° (A), 45°/45° (B), and 90°/90° (C) of hip/knee flexion, with an adjustable strap used to secure the participant's pelvis to the plinth.

fort. Testing position and leg order were randomized for each participant during the 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 3 repetitions for each leg at each of the 3 testing positions. In addition, peak RFD was defined as the greatest increase in force over a rolling 200-millisecond window from contraction onset (increase in resting force of 4 N or greater) until the time when peak force was achieved. Peak RFD over a 200-millisecond window was selected because this has previously been shown to be more reliable than alternative methodologies.[11,13] In order to identify contraction onset, the data were low-pass filtered (10 Hz) using a zero-lag, fourth-order Butterworth filter. To reduce the chance of countermovement influencing RFD, 11 repetitions with a decrease in resting force of 4 N or greater in the 200 milliseconds prior to contraction onset were removed from analysis. Identification and removal of repetitions with a countermovement were performed using custom-written code in R,[20] 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 lying supine on the plinth, arms across their chest, and heels resting in the straps of the apparatus, ensuring 0°/0° of hip/knee flexion (**FIGURE 3A**). From the position used to ascertain resting leg weight, participants moved 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 (**FIGURES 3D** through **3F**, **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 (**FIGURES 3G** through **3I**, **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 (J.H.) had to be satisfied with technique prior to allowing participants to progress to test repetitions.

The bilateral hamstring bridge was performed from 45°/45° of hip/knee flexion, with participants lifting their hips from the plinth until they achieved a straight line from their shoulders to their knees, before returning to the starting position (**FIGURES 4A** through **4C**, **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° of hip/knee flexion (**FIGURES 4D** through **4F**, **ONLINE VIDEO**). The speed of each repetition was controlled by a metronome to ensure a 3-second-up (concentric) and a 3-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 (J.H.) 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 normalized 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 that 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 at which force exceeded resting leg weight for the bilateral variation, or 2 times resting leg weight for the unilateral variation. The end of a rep-

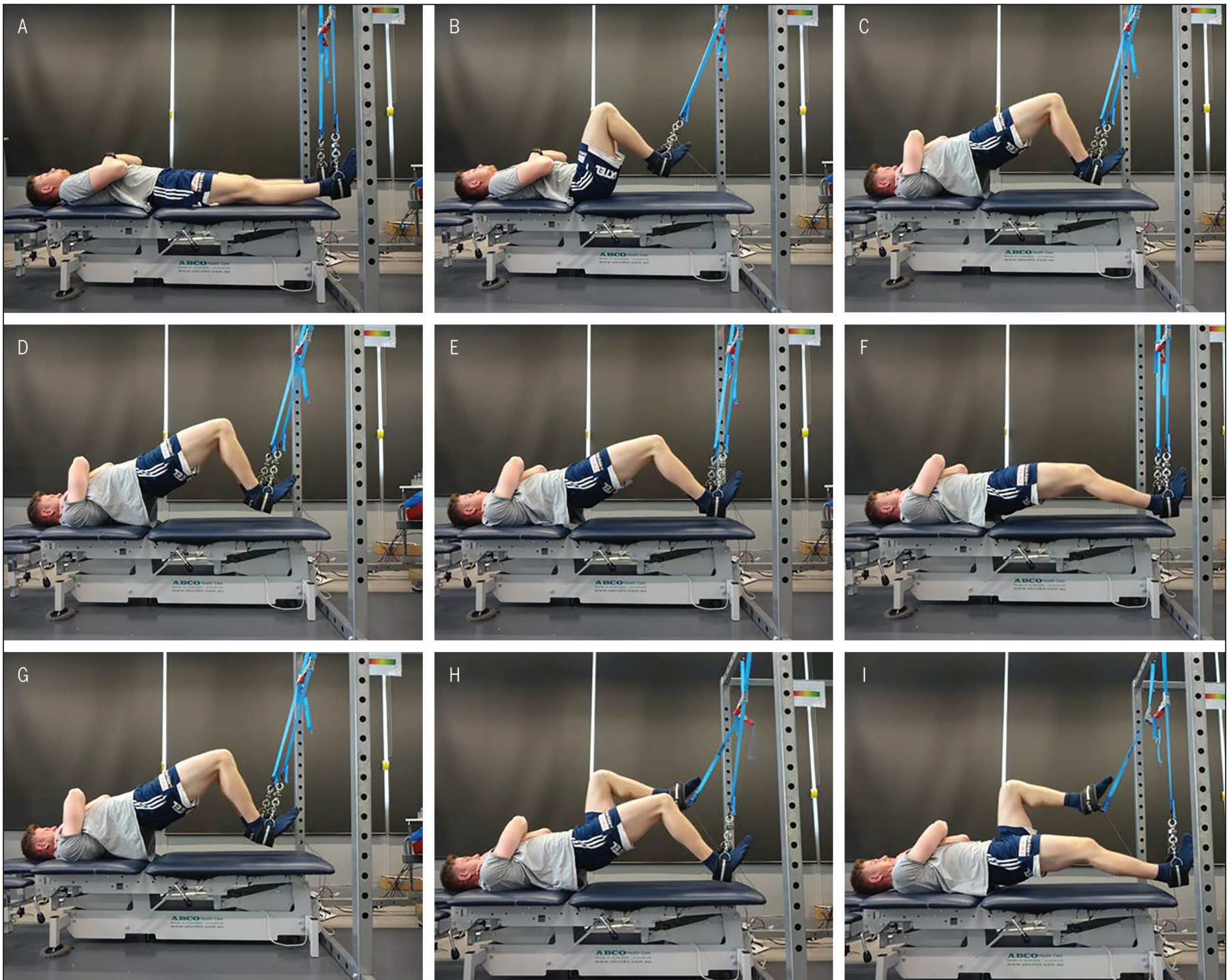

FIGURE 3. Position used to ascertain resting leg weight (A); participant getting into the starting position for the eccentric slider (B and C); eccentric phase of the bilateral eccentric slider (D-F); eccentric phase of the unilateral eccentric slider (G-I).

etition for both the eccentric slider and hamstring bridge was calculated as the point at which force dropped below resting leg weight for each leg independently for the bilateral variation, and 2 times resting leg weight for the unilateral variation. Force impulse was calculated for each repetition, with the average of the 3 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-retest reliability, descriptive statistics for all measures from the dominant and nondominant legs of the control group across 3 visits were screened for normal distribution using the Shapiro-Wilk test in SPSS Version 23.0.0.3 (IBM Corporation, Armonk, NY). Intraclass correlation coefficient (ICC), typical error (TE), and typical error as a coefficient of variation (TE%) were calculated using a custom spreadsheet, with log-transformed data reported for nonnormally distributed measures.[9] Based on previous studies of similar test-retest reliability data,[15,26] an ICC of 0.90 or greater was considered to be high, between 0.80 and 0.89 moderate, and 0.79 or less poor. Minimum detectable change at a 95% confidence interval (MDC_{95}) was calculated as $TE \times 1.96 \times \sqrt{2}$.

Within each group, between-leg comparisons were performed using data from the second visit, to account for an anticipated learning effect from visits 1 to 2. The magnitudes 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.[20] A Cohen's *d* of

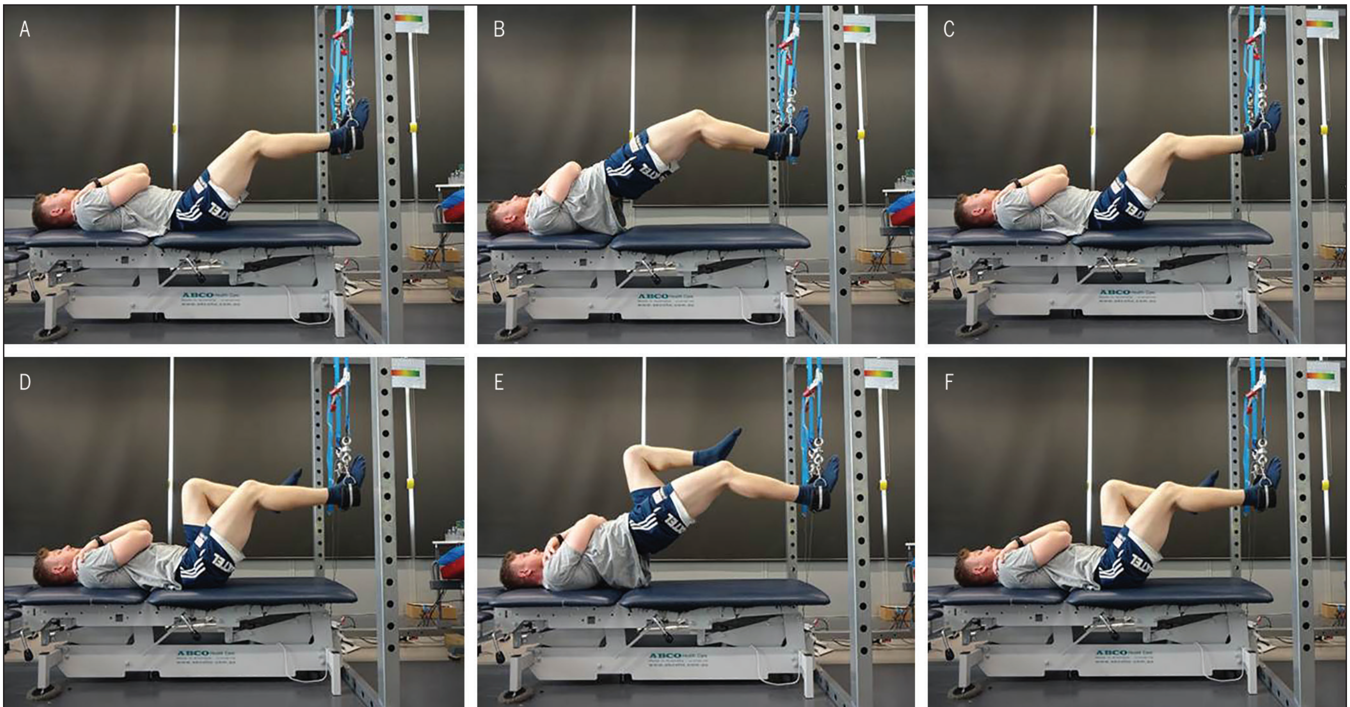

FIGURE 4. Bilateral hamstring bridge from start (A), mid (B), and end (C) repetition positions; unilateral hamstring bridge from start (D), mid (E), and end (F) repetition positions.

≥0.8 was considered large; ≥0.5 and <0.8 moderate; ≥0.2 and <0.5 small, and <0.2 trivial. Where the 90% CI overlapped both the positive (≥0.2) and negative (≤–0.2) thresholds of a small effect simultaneously, effects were defined as unclear.[2] To provide a relative comparison of between-leg differences across all measures, asymmetry was calculated as the nondominant 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 the **APPENDIX** (available at www.jospt.org).

RESULTS

For clarity, all data are reported as mean ± SD unless otherwise stated. The participants' age, stature, and mass were, respectively, 24 ± 4 years, 178 ± 7 cm, and 79 ± 10 kg in the control group and 24 ± 4 years, 182 ± 8 cm, and 86 ± 9 kg in the previous HSI group. Median time from most recent HSI was 9 months (range, 1-15 months).

Test-retest reliability ranged from moderate to high for isometric strength (ICC = 0.87-0.92; TE%, 6.2-8.1) and peak RFD (ICC = 0.88-0.95; TE%, 9.9-12.4) across the 3 positions assessed and for mean force impulse during the unilateral eccentric slider (ICC = 0.87-0.90; TE%, 16.4-17.4). Mean force impulse during the bilateral eccentric slider was moderately reliable (ICC = 0.83-0.87; TE%, 20.2-21.2) and ranged from poor to high during the unilateral (ICC = 0.78-0.92; TE%, 4.8-7.1) and poor to moderate during the bilateral (ICC = 0.57-0.81; TE%, 8.5-13.8) variations of the hamstring bridge. All test-retest reliability data can be found in the **TABLE**.

Among participants 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, –1.97), isometric strength at 0°/0° (*d* = –1.06; 90% CI: –0.18, –1.93) and 45°/45° (*d* = –0.88; 90% CI: –0.02, –1.74), as well as peak RFD at 45°/45° (*d* = –0.88; 90% CI: –0.02, –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, –1.59), isometric strength at 90°/90° (*d* = –0.69; 90% CI: 0.15, –1.54), and mean force impulse during the bilateral bridge (*d* = –0.65; 90% CI: 0.19, –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, –1.04) and isometric strength (*d* = –0.40; 90% CI: 0.15, –0.96). All other between-leg differences were unclear (**APPENDIX**), 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 (1) the novel apparatus was moderately to highly reli-

TABLE **Test-Retest Reliability of the Dominant and Nondominant Legs in the Control Group**

Measure	Visit 1*	Visit 2*	Visit 3*	ICC†	TE†	TE%†	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° nondominant	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° nondominant	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° nondominant	341 ± 70	334 ± 67	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° nondominant	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° nondominant	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° nondominant	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 nondominant	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 nondominant	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 nondominant	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 nondominant	13.9 ± 2.2	14.0 ± 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 coefficient; MDC_{95}, minimal detectable change at 95% confidence level; RFD, rate of force development; TE, typical error; TE%, typical error as a coefficient of variation.
**Values are mean ± SD.*
†Values in parentheses are 95% confidence interval.
‡Indicates ICC taken from log-transformed data due to nonnormal distribution.

able when measuring isometric knee flexor strength and peak RFD across 3 positions, as well as for mean force impulse during an eccentric slider; and (2) 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-retest 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,[21,26] 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.[21,26]

The supine testing position also enabled analysis of isometric RFD, as the force output could be detected from a position of complete rest, allowing for a more accurate identification of contraction onset and countermovement.[11] Peak RFD over a 200-millisecond window was analyzed, 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 in addition 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

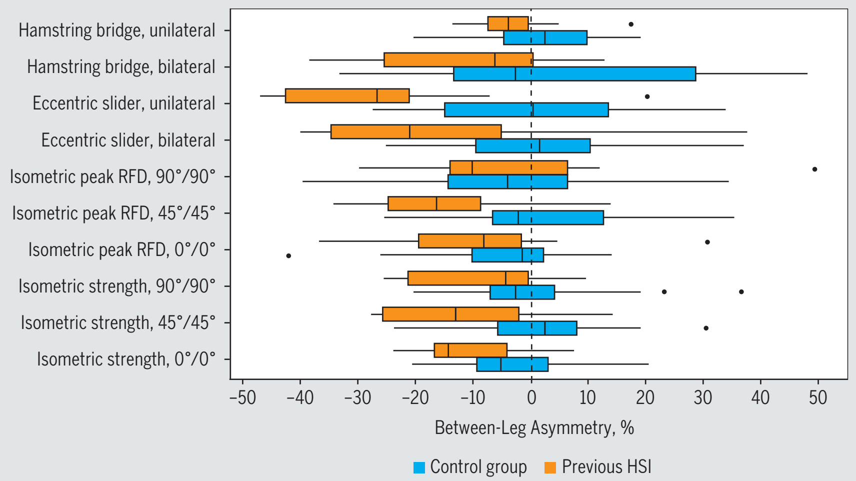

FIGURE 5. Median (middle line) and interquartile range (box) of between-leg asymmetry (percent) for all measures in each group, with whiskers extending 1.5 times the interquartile range from quartiles 1 and 3, respectively, and dots indicating outliers more than 1.5 times the interquartile range from the box. Negative values indicate between-leg asymmetry in favor of the dominant or contralateral uninjured leg in the control and previous HSI groups, respectively. Abbreviations: HSI, hamstring strain injury; RFD, rate of force development.

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 2 exercises, the eccentric slider and hamstring bridge. While independent knee flexor force output of the left and right legs has 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 2 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. 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 utilized commercially available equipment that is relatively inexpensive (costs less than $1000) 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[20] will allow for simpler automated analysis, improving potential for clinical utility.

The current study has some limitations. First, the study included recreationally active participants who performed a minimum of 2 days of physical activity per week; however, the type, volume, and intensity of exercise beyond these minimum requirements were not controlled for. Second, 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. Third, as with any retrospective investigation, it cannot be known whether the between-leg deficits seen in the previous HSI group were a result or cause of initial injury. Fourth, it is acknowledged that muscles such as the gastrocnemius and gracilis also contribute to knee flexor force output in addition to the hamstrings, while 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 rate of force development, and mean force impulse during an eccentric slider, with large between-leg deficits seen in previously injured hamstrings for these measures.

IMPLICATIONS: Clinicians and researchers may implement such a novel apparatus to monitor knee flexor strength during hamstring strain injury (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 limit 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.

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APPENDIX

Between-leg asymmetry (percent); effect sizes, reported as Cohen's *d* with a ±90% confidence interval; and 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 favor of the dominant or contralateral uninjured leg in the control and previous HSI groups, respectively.

Group/Measure	Asymmetry*	Cohen *d*†	Raw *P* Value	Adjusted *P* Value
Control (n = 20)				
Isometric strength at 0°/0°	–2.8 ± 9.2	–0.40 (0.15, –0.96)	.088	.790
Isometric strength at 45°/45°	1.6 ± 12.2	0.05 (0.60, –0.49)	.809	1.000
Isometric strength at 90°/90°	0.6 ± 14.2	–0.02 (0.53, –0.56)	.937	1.000
Peak RFD at 0°/0°	–5.7 ± 13.1	–0.48 (0.07, –1.04)	.045	.446
Peak RFD at 45°/45°	1.9 ± 14.9	0.04 (0.59, –0.51)	.857	1.000
Peak RFD at 90°/90°	–3.3 ± 15.8	–0.24 (0.32, –0.81)	.305	1.000
Eccentric slider, bilateral	1.6 ± 16.1	–0.13 (0.43, –0.70)	.573	1.000
Eccentric slider, unilateral	0.3 ± 17.8	0.01 (0.56, –0.53)	.962	1.000
Hamstring bridge, bilateral	4.4 ± 22.9	0.13 (0.67, –0.42)	.582	1.000
Hamstring bridge, unilateral	1.9 ± 10.6	0.12 (0.67, –0.42)	.584	1.000
Previous HSI (n = 10)				
Isometric strength at 0°/0°	–10.8 ± 10.0	–1.06 (–0.18, –1.93)	.009	.078
Isometric strength at 45°/45°	–12.5 ± 14.5	–0.88 (–0.02, –1.74)	.021	.168
Isometric strength at 90°/90°	–8.6 ± 12.5	–0.69 (0.15, –1.54)	.056	.279
Peak RFD at 0°/0°	–9.2 ± 18.9	–0.75 (0.10, –1.59)	.043	.256
Peak RFD at 45°/45°	–14.5 ± 15.7	–0.88 (–0.02, –1.74)	.021	.168
Peak RFD at 90°/90°	–2.5 ± 22.1	–0.40 (0.42, –1.23)	.234	.404
Eccentric slider, bilateral	–13.8 ± 27.0	–0.64 (0.20, –1.48)	.074	.279
Eccentric slider, unilateral	–26.0 ± 20.7	–1.09 (–0.20, –1.97)	.007	.075
Hamstring bridge, bilateral	–11.0 ± 18.3	–0.65 (0.19, –1.49)	.069	.279
Hamstring bridge, unilateral	–2.9 ± 9.0	–0.44 (0.39, –1.26)	.202	.404

Abbreviations: HSI, hamstring strain injury; RFD, rate of force development.
**Values are mean ± SD percent.*
†Values in parentheses are 90% confidence interval.