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"It is possible and imperative that we learn
A brave and startling truth."
— Maya Angelou

As 2019 draws to a close, it is the right time for the *JOSPT* editors to say thank you, and celebrate all who contributed to the *Journal* this year. It is your knowledge, willingness to share, and commitment to quality that allow *JOSPT* to publish high-quality content to help rehabilitation clinicians help patients and athletes.

Congratulations to the authors whose work we published in *JOSPT* this year. Your work is what helps *JOSPT* fulfill our mission to publish rigorous content.

Thank you to the authors of invited Editorials and Viewpoints, who provided thought-provoking contributions that help us fulfill the second half of our mission: to promote application of quality content to movement-related health.

The members of the 2019 Editorial Board (including 14 Associate Editors, 15 Special Features Editors, 88 International Editorial Review Board members, 4 Statistical Consultants, and 1 Read-for-Credit Coordinator) are listed on the masthead of the *Journal* each issue—and are vital to the success of the *Journal*.

Finally, we recognize the contributions made by all who have been members of *JOSPT* peer-review teams in 2019. Thank you for sharing your expertise and time to provide constructive feedback. All manuscript and Musculoskeletal Imaging reviewers who contributed to peer review in 2019 are listed below.

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"He aha te mea nui i te ao? He tāngata, he tāngata, he tāngata.
What is the most important thing in the world? People, people, people."
— Māori proverb

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Clinical Interpretation of the Neck Functional Status Computerized Adaptive Test

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Patient-reported outcome measures (PROMs) are administered directly to patients to capture their perceptions of different health-related dimensions[1,5] and to translate the patient's experience into a measurable construct that can be used to monitor health status over time.[12,47,49] Increasingly advocated as necessary components of an overall strategy to improve health care,[2,14] PROMs may be used in conjunction with other information to assess the value of care[48,50,51] and the progress of individual patients during care. One of the most common complaints for which patients seek physical therapy is neck pain. These patients are known to be the second largest group (after those with low back pain) of outpatients receiving care due to musculoskeletal impairments.[9,17]

BACKGROUND: Clinical interpretation of patient-reported outcome measures is an essential step in patient-centered care. Interpretation of scores derived from the Neck Functional Status Computerized Adaptive Test (NFS-CAT) has not been studied.

OBJECTIVES: To (1) assess the reliability of point estimates and improvement scores, (2) determine thresholds of minimal clinically important improvement (MCII), and (3) develop a functional staging model to facilitate clinical interpretation of NFS-CAT scores.

METHODS: A secondary retrospective cohort analysis was performed using data from patients aged 14 to 89 years who started an episode of care for neck impairments during 2016-2017 and completed the NFS-CAT at admission. The reliability of point estimates and of improvement scores was derived from the NFS-CAT standard error of measurement. The MCII was estimated by combining distribution- and anchor-based approaches. A functional staging model was developed to describe clinical meaningfulness of the quantitative scores provided by the NFS-CAT.

RESULTS: Of 250 741 patients who completed the NFS-CAT at admission (mean ± SD age, 54 ± 16 years; 65% female), 169 039 (67%) also completed the NFS-CAT at discharge. The standard error of measurement was stable across the measurement continuum, ranging from 3.7 to 3.9 NFS-CAT points. Minimal detectable improvement was 6.8 points at the 90% confidence level. The estimate of the MCII was 8.1 points, with more change points needed to achieve the MCII for patients with lower baseline scores. Large rates of functional staging change during treatment were observed, demonstrating responsiveness of the functional staging model.

CONCLUSION: This study demonstrated how the NFS-CAT can be interpreted to better assist clinicians and patients with neck impairments during outpatient rehabilitation.

LEVEL OF EVIDENCE: Therapy, level 2b.
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KEY WORDS: *clinical interpretation, functional status, neck pain, patient-reported outcome measures, physical therapy*

Prevalence estimates from epidemiologic studies on neck pain (defined as pain in the neck, with or without pain referred into one or both upper limbs, that lasts for at least 1 day) have a mean 1-year prevalence range of 23%[27] to 37%[11] and a mean lifetime prevalence of 49%.[11] Consequently, neck pain is recognized as a global health care burden.[26,31] Assessment of functional status using PROMs in patients with neck pain is an essential step in addressing this burden, provided the scores can be interpreted in clinically useful ways to inform patient-centered clinical decision making.

The current study builds on previous development work on the Neck Functional Status Computerized Adaptive Test (NFS-CAT).[62] Research findings supported unidimensionality and local indepen-

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dence of responses from 439 patients to all 28 items of the NFS-CAT item bank. Items were found to have negligible differential item functioning, and NFS-CAT scores had no ceiling or floor effects. The computerized adaptive test (CAT) scores, derived from an average of 6.6 items per CAT (median, 6), had a precision similar to that of scores based on all (n = 28) items of the CAT bank. Clinically meaningful interpretations of the NFS-CAT have not been studied. Therefore, the purpose of this study was to provide a set of estimates helpful in clinical interpretation of individual scores derived from the NFS-CAT, including (1) the reliability of point estimates and improvement scores at different levels of confidence, (2) thresholds of minimal clinically important improvement (MCII) based on distribution- and anchor-based estimates, and (3) a functional staging model to facilitate interpretation of the clinical meaningfulness of NFS-CAT scores.

METHODS

Design and Sample Selection

The authors conducted a retrospective observational study using data collected routinely in outpatient rehabilitation therapy clinics in the United States. Participating clinics routinely collect PROMs of functional status using the Patient Inquiry software developed by Focus On Therapeutic Outcomes, Inc (FOTO; Knoxville, TN).[61] The majority of clinics (96%) that utilize FOTO data for outcome measurement tracking are private practice or hospital-based outpatient clinics.[4] Patients aged 14 to 89 years were included if they (1) started an episode of care from January 1, 2016 to December 31, 2017, (2) identified a primary complaint corresponding to the neck region of the body at admission, and (3) were discharged from therapy as determined by the completion of a staff discharge survey.

Data Collection

The FOTO system collects a standard set of data that includes responses to PROMs, patient demographics, and patient health characteristics.[61] The PROM data were collected using the NFS-CAT, which was previously developed using FOTO's CAT Development and Testing Software Version 2.1.0.[19] The administration of the CAT is tailored to the individual patient, with item selection based on patient responses and the difficulty of yet-to-be-administered items.[15,16,38] This reduces the number of administered items, improving efficiency of PROM data collection while reducing associated patient burden.[18] For each patient, the CAT begins with an item of medium difficulty. Based on the patient's response to that item, the CAT algorithm obtains a provisional functional status estimate for the patient, as well as the estimate's standard error of measurement (SEM).[37] The CAT next selects the item from the item bank that best targets the respondent's provisional estimate of functional status, that is, the item that best discriminates among people whose functional status is closest to the provisional estimate. After the patient responds to this second item, the provisional estimate is updated, as is the SEM. This continues until one of the CAT stopping rules is satisfied or until all items from the item bank have been administered. Details of the NFS-CAT were described previously.[62] The NFS-CAT stopping criteria are (*a*) the SEM of the provisional ability estimate is less than 4 points on the 0-to-100 NFS-CAT scale, and (*b*) the mean absolute change in the respondent's provisional estimate for the last 3 items was less than 1 unit.[20] The functional status estimate obtained when the CAT stops is the respondent's final score (0-100), with higher scores indicating better function, with its associated SEM.

Assessment of Patient Selection Bias

Patient selection bias could occur if patients who improve more (or less) are more likely to complete follow-up PROMs. To assess the potential for systematic patient selection bias at discharge, the characteristics of patients with incomplete (admission only) and complete (admission and discharge) PROM data were compared. If a systematic patient selection bias at discharge existed, it was expected that patients with complete PROM data would have higher values or frequencies of characteristics associated with better outcomes compared to those with incomplete PROM data. Chi-square tests were used for analysis of categorical data, and *t* tests were used for continuous data. Statistical significance was set at an alpha of .05 for all tests. Comparisons included the following patient characteristics known to be associated with outcomes: NFS-CAT score at admission, age, number of comorbidities, sex, acuity as measured by number of days from onset of the treated condition, type of payer, surgical history as measured by number of related surgeries, exercise history, use of medication at intake for the treatment of neck pain, and having received previous treatment for neck pain.[8-10,17]

Reliability of Point Estimates

Reliability-based estimates were calculated using NFS-CAT data collected at admission. Reliability of individual scores was based on the SEM associated with the final estimate of ability obtained during the CAT administration, as described above. The scale-level reliability of the NFS-CAT was summarized as 1 – baseline SEM^2/baseline SD^2, where baseline SEM is the median SEM for the NFS-CAT in a range from −3 to +3 SDs, and baseline SD is the SD of NFS-CAT scores at admission.[46] Reliability at different levels of scores was calculated using median SEMs of individual scores by quartiles of NFS-CAT estimates at admission. This approach to estimating reliability is more conservative than estimates based on administration of the full bank of items, as higher reliability may also result from administering more correlated items.[43] Therefore, this approach is more valid for CAT-based PROM administration when not all items are administered. The confidence interval

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(CI) defines the probability that the true population mean falls within score intervals drawn from multiple samples.[41,44] Confidence intervals are narrower or wider depending on the level of confidence preferred, and the preferred level of confidence is subjective. The clinician should ask, "How confident do I want to be about where a patient's true score lies?" Reported here are score ranges that provide different CIs, including the 68% CI, which is equivalent to 1 SEM, and 80%, 90%, and 95% CIs. The CIs were computed by multiplying the SEM by the corresponding z value from the standard normal deviate associated with the desired confidence level. For example, for a 95% CI, the SEM was multiplied by 1.96. To evaluate whether CIs for point estimates differed at different scale ranges, CIs for the full range of scores and by quartiles of NFS-CAT scores at admission were calculated. Because the level of SEM is used as one of the CAT stopping rules, we assessed number of items administered and the corresponding time (minutes) to complete the NFS-CAT associated with the SEM, using a computerized time log. Log-off errors, or abandoned surveys completed at a later stage, may have created very short or very long (eg, hours) time logs. Therefore, we included only cases within the 2.5 to 97.5 percentiles to exclude outliers.

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Reliability of Improvement Scores

In addition to the interpretation of a point estimate, clinicians are faced with the need to interpret improvement scores during treatment. In most studies, thresholds are estimated for minimal detectable change, which requires a 2-tailed hypothesis test (change for the better and change for the worse).[64-68] However, because the expectation in physical therapy is that most patients will get better following treatment, the interpretation of score improvement rather than score change may be more appropriate. Thus, 1-tailed CIs at 90% and 95% levels of confidence were calculated, which are equivalent to 80% and 90% 2-sided hypothesis tests, respectively. The authors refer to the resulting CIs as the minimal detectable improvement (MDI) at different levels of confidence (ie, MDI_{90}, MDI_{95}). Because change involves at least 2 measured points, a factor of 2 (ie, for 2 measurements) comes into play; therefore, reliability-based estimates of MDI were calculated by multiplying the SEM of the difference ($SEM_{difference}$ = SEM × $\sqrt{2}$) by the appropriate z value.[56] Minimal detectable improvements were calculated for the full range of scores and by quartiles of NFS-CAT scores at admission.

Distribution- and Anchor-Based Estimates of MCII

We calculated 2 commonly used distribution-based estimates of MCII, including 1 SEM and 0.5 SD of NFS-CAT scores at baseline.[42,69] Because distribution-based estimates of important change rely on a statistical criterion, namely the score's standard deviation, they are sample dependent. Anchor-based methods for assessing important change have been proposed to reduce sample dependency.[42] However, anchor-based methods that rely on retrospective assessment of change have also been criticized as being subject to recall bias.[54] Therefore, combining distribution- and anchor-based approaches and triangulating the results have been recommended.[3,6,30,52,70]

To incorporate the patient's perspective on the clinical importance of NFS-CAT score change, we used a global rating of change (GROC) as the external anchor. The GROC used by FOTO includes 1 question with a 15-point scale for the degree of change (–7 to +7), with zero representing no change.[33] Data from patients who completed both the NFS-CAT and the GROC at discharge were used for this analysis. During most of the data-collection period, completion of the GROC was mandatory at each completion of a follow-up NFS-CAT. Therefore, there was essentially no potential for patient selection bias related to the completion of the GROC. To confirm this, we compared characteristics of patients with complete outcomes data who had or did not have GROC data at discharge, using the same methods as described above. We assessed meaningful change thresholds of MCII by dichotomizing patients into those who did and did not improve by an important amount, using a GROC score of 3 or more. We chose a threshold of 3 or more (3 is "somewhat better") because previous studies showed that this cut score provided adequate assessment of MCII.[22-24] Because of the large body of evidence that MCII levels are dependent on baseline functional status,[13,21-25,36,45,53,57,63-68] we also estimated MCII by quartiles of baseline functional status. Using receiver operating characteristic analyses, MCII cut points were identified by selecting the functional status change score with the largest average specificity and sensitivity values. Percent of improved patients, MCIIs and their 95% CIs, areas under the receiver operating characteristic curve and their 95% CIs, and percentage of patients whose functional status change was equal to or greater than the MCII were used to describe the receiver operating characteristic results. Two a priori criteria were set for MCII acceptance: (1) the NFS-CAT change scores were adequately correlated with the GROC scores (ie, Spearman rho of 0.3 or more), and (2) MCII was equal to or larger than the SEM, so that it represented an improvement that equaled or exceeded measurement error.

Functional Staging

A functional staging model was developed using methods described previously.[34,65-68] Functional staging is used to describe clinical meaningfulness of the quantitative scores provided by a measure. Score-based functional abilities are described for patients at different score levels.[34] Based on the original response category thresholds,[62] we graphically displayed a functional staging chart that portrayed the expected response to a given item as a function of the underlying ability (ie, functional status).[62] Three experienced clinicians (D.D., M.W., D.H.) reviewed the output and reached consensus on expected performance of patients at 5 hierarchical stages of neck function and on the 4 cut scores that defined the 5 stages, representing limited self-care and light, moderate, high, and vigorous activity levels (**FIGURE 1**). This figure shows items listed in descending order of difficulty. Beneath the figure is the NFS-CAT score continuum, ranging from 0 to 100 (higher values represent better perceived functioning) and separated by horizontal lines to define 5 levels of functional staging, from stage 1 (left, lower functioning) to stage 5 (right, higher functioning). Using the functional staging method, we can compare the patient's NFS-CAT score to the functional stages to improve interpretation of the patient's score. Full item descriptions are provided in **TABLE 1**.

To test the clinical clarity and interpretability of the staging model definitions, a validity test was conducted to evaluate concurrence between clinician-based classifications and score-based classifications. We identified 6 NFS-CAT surveys completed by actual patients, 3 at intake and 3 at discharge. Each of the 6 completed surveys had a score associated with it and, thereby, a score-based functional classification. To find out whether these score-based classifications concurred with clinician impressions, we recruited 10 physical therapists who were not on the research team but who had experience both in treating patients with neck impairments and in working with CAT-based PROMs. The clinicians reviewed the staging definitions and chart. Next, they reviewed the completed surveys, blind to their associated scores, and classified surveys based on the functional staging system. At this point, we had 6 completed surveys and their actual scores. We also had 10 clinician-based classifications for each of 6 surveys (60 total classifications). Next, we compared the score- and clinician-based classifications. We operationalized classification concurrence as a survey whose score was within the score range specified by the functional staging system ± SEM beyond the upper and/or lower threshold (to account for measurement error). For example, if a therapist assigned stage 2 to a score included in the upper range of stage 1, but the score plus its SEM fell within stage 2, then the assignment was considered concurrent.

The average percentage of successful stage selections was calculated for each therapist. Agreement among therapists was assessed using the Krippendorff al-

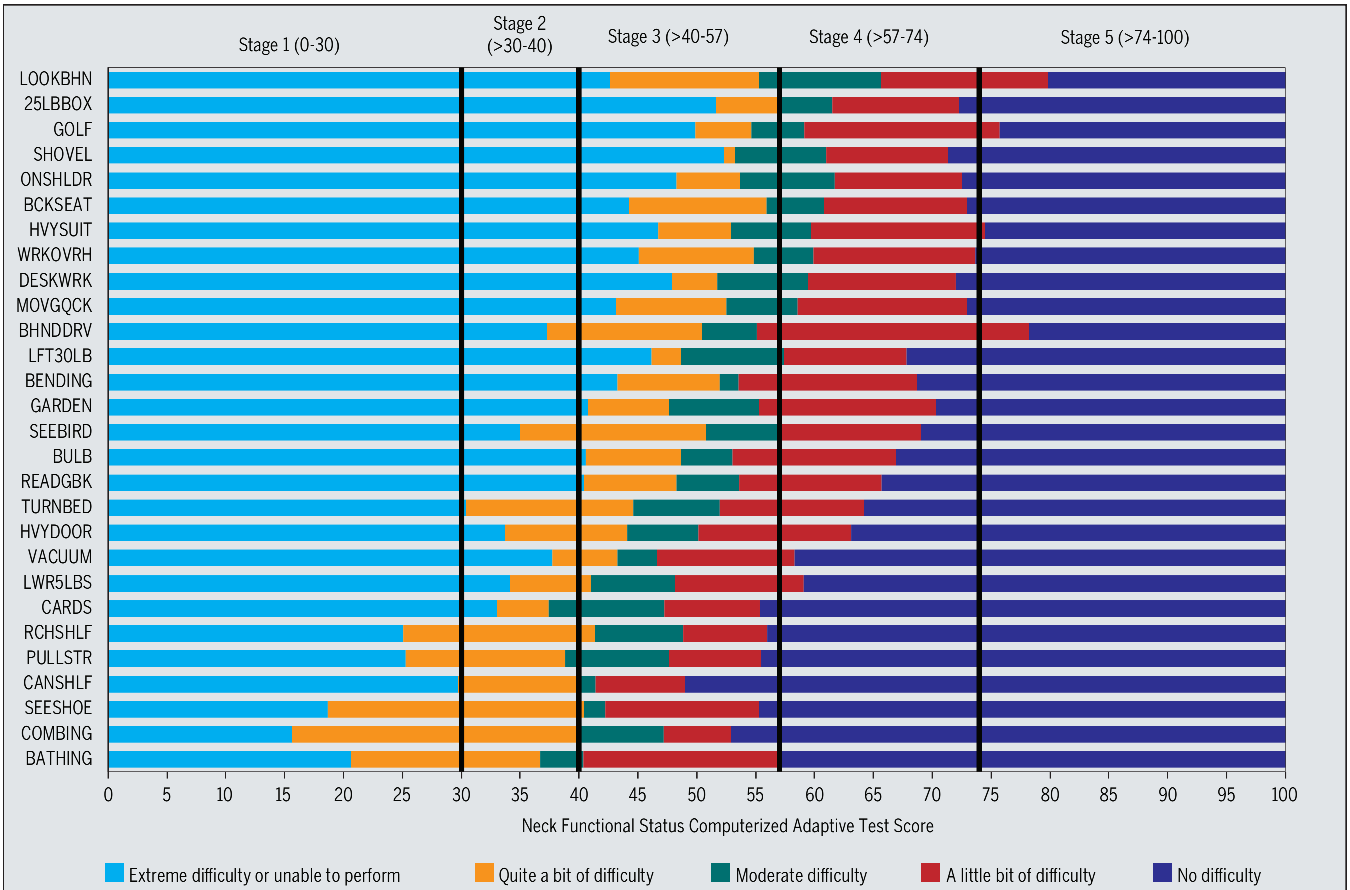

FIGURE 1. Functional staging chart. Item descriptions are provided in **TABLE 1**. The functional staging chart defines 5 hierarchical functional stages. The black vertical lines represent the 4 cut scores defined along the measurement continuum. The chart illustrates the expected response to a given item at each functional stage. For example, at a score of 35, which corresponds to stage 2, the response to item RCHSHLF (reaching a shelf that is at shoulder height) is expected to be "quite a bit of difficulty."

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pha coefficient.[35] To further assess the functional staging model's responsiveness, we visualized the rates of functional staging changes during treatment using a Sankey diagram. Large rates of change during treatment would support the model's responsiveness.

All analyses were conducted using Stata Version 14 (StataCorp LLC, College Station, TX). This study was approved by the Institutional Review Board of Northwestern University. Because normal treatment was not altered, patient informed consent was not required.

RESULTS

Patient Sample, Measure Coverage, and Responsiveness

The primary sample included 250 741 patients who started an episode of care from January 1, 2016 through December 31, 2017 and completed the NFS-CAT at admission (mean ± SD age, 54 ± 16 years; 65% female). Of these, 169 039 patients also completed the NFS-CAT at discharge, resulting in a completion rate[7] of 67% (**FIGURE 2**). Complete GROC measures at discharge were available from 126 026 patients, representing 75% of those who had complete outcomes data. Patients' scores were normally distributed along the measure continuum at admission, with a mean of 52, SD of 12.3, and median of 52. There were no ceiling or floor effects (less than 1% of patients had a score of 0 to 5 or 95 to 100, combined, supporting previous results).[62] The NFS-CAT had an effect size of 0.99 as measured by Cohen's d,[32] dividing the change score from admission to discharge by the standard deviation at baseline (**TABLE 2**).

Assessment of Patient Selection Bias

The comparison of patients with complete and incomplete outcomes data is presented in **TABLE 2**. No differences between groups were identified for admission functional status and sex. Differences were identified for number of comorbidities, acuity, exercise history and surgical history, and receiving previous treatment for neck pain. Compared to those with incomplete data, patients with complete outcomes data were 3 years older, had a higher rate of Medicare Part B participation for those aged 65 years or older, and used less medication related to their neck pain at admission. When comparing patients who had complete outcomes data with (n = 126 026) or without (n = 43 013) GROC data, only small differences were identified: baseline functional status (51.9 versus 52.0, respectively; $P = .016$), some payer categories (data available on request; $P<.001$), and exercise history (seldom or never, 34.8% versus 35.5%, respectively; $P = .001$).

Reliability of Point Estimates

The scale-level reliability of the NFS-CAT was 0.91. Median SEMs of individual scores are reported in **TABLE 3**. Also included are the 80%, 90%, and 95% CIs for point estimates across the full score range and by quartiles of NFS-CAT scores at admission. The SEMs were stable across the measurement continuum, ranging from 3.7 to 3.9 NFS-CAT points, which corresponds to 7.2 to 7.6 points at the 95% confidence level. After removing outliers due to seemingly implausible amounts of time for CAT completion (ie, 5-30 seconds or 18.6 minutes to 24 hours), the median time (minutes) for CAT completion and the number of

TABLE 1 Item Descriptions*

Item		Short Description
1.	LOOKBHN	Turning to look behind you
2.	25LBBOX	Placing a 25-lb box on a shelf overhead
3.	GOLF	Performing forceful recreational activities
4.	SHOVEL	Using a shovel to dig a hole in the dirt
5.	ONSHLDR	Carrying objects on your shoulders
6.	BCKSEAT	Touching an object on the back seat of a car
7.	HVYSUIT	Lifting and carrying a heavy suitcase
8.	WRKOVRH	Work overhead for more than 2 minutes
9.	DESKWRK	Light desk work for 8 hours
10.	MOVGQCK	Moving your head quickly
11.	BHNDDRV	Turning to look behind you to drive a car
12.	LFT30LB	Lifting medium weights (20-30 lb) from the floor
13.	BENDING	Bending over to clean a bathtub
14.	GARDEN	Performing garden or yard work
15.	SEEBIRD	Looking up to see a bird
16.	BULB	Changing a light bulb overhead
17.	READGBK	Sitting and reading a book for 1 hour
18.	TURNBED	Turning over in bed
19.	HVYDOOR	Pulling or pushing a heavy door
20.	VACUUM	Using a vacuum cleaner
21.	LWR5LBS	Lowering a lightweight object (1-5 lb) from a top shelf
22.	CARDS	Performing low-effort recreational activities
23.	RCHSHLF	Reaching a shelf that is at shoulder height
24.	PULLSTR	Reaching for and pulling a fan string
25.	CANSHLF	Placing a can of soup on a shelf overhead
26.	SEESHOE	Looking down to see your shoes
27.	COMBING	Combing or brushing your hair
28.	BATHING	Performing personal care activities

**Items are sorted in descending order of difficulty level.*

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administered items were 1.5 minutes (mean, 2.3; range, 0.5-18.5) and 5 items (mean, 5.5; range, 3-18), respectively.

Reliability of Improvement Scores

The MDIs at different levels of confidence (MDI_{90}, MDI_{95}) for the full range of NFS-CAT scores and by quartiles of scores at admission are presented in **TABLE 4**. As an example of how these data should be interpreted, a patient with an admission score of 40 (first quartile), at the 90% level of confidence, needs to improve by 6.8 NFS-CAT points to exceed measurement error.

Distribution- and Anchor-Based Estimates of MCII

Spearman rank correlation between NFS-CAT change scores and GROC ratings was 0.52. Estimates of MCIIs were larger than the SEM, except for patients with upper-quartile baseline functional status scores (**TABLE 5**). A half SD of baseline functional status scores was 6.3 points (**TABLE 2**). The SEM, percent of improved patients (GROC of 3 or greater), MCII estimates, area under the curve, and percentage of patients whose functional status change was equal to or greater than the MCII are presented in **TABLE 5**. Results are included for the overall score and by baseline NFS-CAT score ranges. The estimate of MCII across the full score range was 8.1 points, while MCII estimates ranged from 15 to 4 NFS-CAT points from the first to fourth quartiles of baseline scores. Thus, more change was needed to achieve MCII for patients with lower baseline functional status, supporting previous results described above.

Functional Staging

The functional staging model's operational definitions are presented in **TABLE 6**, providing a simple guideline to interpret the functional stage levels. An example of a patient's NFS-CAT survey used for the functional staging assessment is presented in **TABLE 7**. The mean success of staging selection was 92%, with a Krippendorff alpha of .92. Percentages of functional staging change from admission to discharge are shown in **FIGURE 3**, demonstrating large rates of functional staging change during treatment. Rates of functional staging change from admission to discharge are presented in **TABLE 8**, with 61% of patients demonstrating a functional staging change.

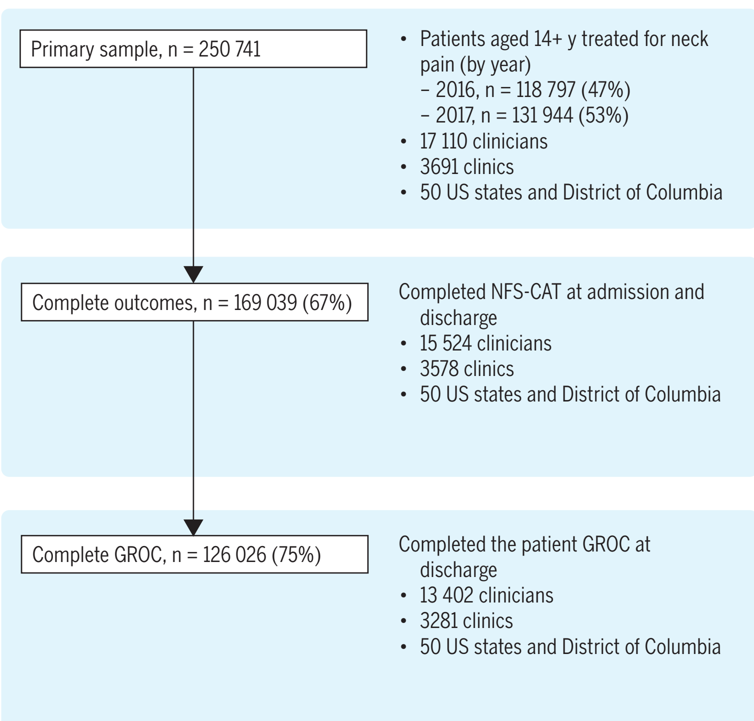

FIGURE 2. Patient sampling. Percentages shown are from the level above. Abbreviations: GROC, global rating of change; NFS-CAT, Neck Functional Status Computerized Adaptive Test.

DISCUSSION

This study provided a set of estimates useful in interpreting scores derived from the NFS-CAT during clinical practice. The SEM range of 3.7 to 3.9 NFS-CAT points (**TABLE 3**) was expected when using a CAT stopping rule of an SEM less than 4 points. This point estimate reliability was associated with a median response burden of 1.5 minutes to complete 5 to 6 items. Clinicians should interpret point estimates accordingly. For example, when considering the patient's functional stage for an admission score of 39, the assigned stage is number 2 (light activity, 30-40 points) (**TABLE 6**). Considering measurement error, there is a possibility that the true functional stage is number 3 (moderate activity). With the CAT, the SEM could be decreased or increased by modifying the SEM stopping rule. If lower error (ie, higher reliability) is desired, more items and time would be needed to reach the adjusted CAT stopping rule. An SEM of less than 4 out of 100, with a scale-level internal consistency reliability of 0.91 while answering a mean of 5.5 items, seems to be well balanced and maintains high accuracy and clinical practicability for routine use in busy clinical settings. The high CAT reliability estimate, lack of ceiling and floor effects, and excellent responsiveness were consistent with findings of Hung et al[28,30] and Moses et al[40] when testing psychometric properties of the Patient-Reported Outcomes Measurement Information System physical functioning CAT and item bank in a similar patient population.[28,30,40]

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The reliability estimates of improvement (MDI) from this study can help clinicians determine whether the patient improved over time by a degree that exceeds measurement error, at different levels of confidence. However, as reliability values of change (or improvement) scores are driven by the measurement's standard error (SEM), they do not provide information on improvement that is important from the patient's perspective. For this, MCII estimates were calculated for the overall score range and by quartiles of NFS-CAT scores at baseline to enhance a patient-specific interpretation of improvement. Patients with lower baseline NFS-CAT scores needed more change to achieve the MCII, which

TABLE 2 Health and Demographic Characteristics of Patients With Complete Versus Incomplete FS Outcomes Data*

Patient Characteristic	Total (n = 250 741)	Complete (n = 169 039, 67%)	Incomplete (n = 81 702, 33%)	*P* Value†
FS score at admission	51.9 ± 12.6 (3-97)	51.9 ± 12.3 (3-96)	51.8 ± 13.1 (3-97)	.205‡
FS score at discharge	NA	64.1 ± 14.8 (3-97)	NA	NA
Age, y	53.6 ± 16.0 (14-89)	54.6 ± 16.2 (14-89)	51.5 ± 15.5 (14-89)	<.001‡
Number of comorbidities§	5.3 ± 3.1 (5, 4)	5.3 ± 3.1 (5, 4)	5.3 ± 3.2 (5, 4)	.004‡
Sex (female), %	65.3	65.2	65.4	.482
Acuity, %				<.001
0-7 d	4.0	4.0	3.9	
8-14 d	6.7	6.9	6.3	
15-21 d	8.4	8.6	8.0	
22-90 d	26.8	27.1	26.1	
91 d to 6 mo	14.0	14.1	14.0	
Over 6 mo	40.1	39.4	41.7	
Payer, %				<.001
Indemnity insurance	3.5	2.9	4.6	
Medicaid	5.7	4.9	7.3	
Medicare Part A	1.2	1.3	1.0	
Medicare Part B (under age 65)	4.0	3.8	4.4	
Medicare Part B (age 65 or above)	18.1	20.6	13.0	
Patient	0.7	0.6	0.8	
Workers' compensation	4.2	4.6	3.5	
Other (litigation, Medicare Part C, school, no charge, early intervention, commercial insurance)	10.7	10.4	11.4	
No fault, auto insurance	4.3	4.6	3.5	
HMO, PPO	47.6	46.3	50.4	
Surgical history, %				<.001
No related surgery	87.7	87.6	87.9	
1 related surgery	9.0	9.2	8.6	
2 related surgeries	2.1	2.1	2.2	
≥3 related surgeries	1.2	1.2	1.3	
Exercise history, %				<.001
At least 3 times/wk	38.1	38.5	37.2	
1-2 times/wk	26.4	26.5	26.4	
Seldom or never	35.4	35.0	36.4	
Medication use at intake, %	50.9	50.3	52.3	<.001
Previous treatment, %	40.0	40.3	39.4	<.001

Abbreviations: FS, functional status; HMO, health maintenance organization; NA, not available; PPO, preferred provider organization.
**Patient characteristics for all included patients (total), patients with FS data at admission and discharge (complete), and patients with FS data at admission only (incomplete). Values are mean ± SD (range) unless otherwise indicated.*
†P values are a result of chi-square tests unless otherwise indicated.
‡P values are a result of t tests.
§Values are mean ± SD (median, interquartile range) due to the skewed distribution.

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is clinically logical and replicates results from similar studies.[58,63-67] For example, a patient with an admission score of 35 points, which is within the first quartile of admission scores, would need to improve by 8.8 points to exceed measurement error at a 95% level of confidence (**TABLE 4**). However, this patient would need 15.2 points to achieve an MCII from the patient's perspective (**TABLE 5**). Interestingly, for patients with high baseline NFS-CAT scores (59-100), an improvement of only 3.7 points was estimated to represent the MCII, which was similar to, and slightly lower than, the corresponding SEM of 3.9 points. When MCII is less than change that falls within measurement error, clinical interpretation is challenging. Stratford and Riddle[60] offered a valid argument that emphasized the differences in scope between these 2 estimates,[60] suggesting that, for patient-centered clinical interpretation of change, MCII values are preferred. However, reliability-based estimates of change are useful when anchor-based estimates are not available. It is important to acknowledge that achieving the MCII, by definition, represents minimal improvement as perceived by the patient, and therefore should not be interpreted as a patient-centered goal or an end point of the episode of care. In a recent study, Hung et al[29] found that values of important change derived by combining distribution- and anchor-based methods among patients with spinal conditions varied and were highly dependent on the method used.[29] They suggested lower values for screening purposes and higher values for outcome measures. Goal setting should also consider risk-adjusted predicted change when available,[10] and achieving or exceeding its corresponding predicted functional stage at discharge, as well as the meeting of patient-specific functional goals.[55]

TABLE 3 RELIABILITY OF POINT ESTIMATES*

Baseline FS Score	SEM†	80% CI	90% CI	95% CI
Overall score range	3.7	4.8	6.1	7.3
First quartile (FS, 0-43.8)	3.8	4.8	6.2	7.4
Second quartile (FS, >43.8-51.9)	3.7	4.7	6.0	7.2
Third quartile (FS, >51.9-59.3)	3.7	4.7	6.0	7.2
Fourth quartile (FS, >59.3-100)	3.9	4.9	6.4	7.6

Abbreviations: CI, confidence interval; FS, functional status; SEM, standard error of measurement.
**Confidence in point estimates across the full score range and by quartiles of Neck Functional Status Computerized Adaptive Test scores at admission (n = 169 039).*
†Median standard error from the computerized adaptive test surveys.

TABLE 4 RELIABILITY OF IMPROVEMENT SCORES*

Baseline FS Score	MDI_{90}†	MDI_{95}‡
Overall score range	6.8	8.7
First quartile (FS, 0-43.8)	6.8	8.8
Second quartile (FS, >43.8-51.9)	6.6	8.5
Third quartile (FS, >51.9-59.3)	6.6	8.5
Fourth quartile (FS, >59.3-100)	7.0	9.0

Abbreviations: FS, functional status; MDI, minimal detectable improvement (1 tailed).
**Confidence in improvement estimates across the full score range and by quartiles of Neck Functional Status Computerized Adaptive Test scores at admission (n = 169 039).*
†Calculated at the 90% confidence interval.
‡Calculated at the 95% confidence interval.

TABLE 5 ANCHOR-BASED ESTIMATE OF MCII*

Baseline FS Score	SEM†	Improved (GROC, ≥3), %	MCII/ROC Cut Point‡	AUC‡	MCII or Greater, %
Overall score range	3.7	82.4	8.1 (7.1, 9.0)	0.75 (0.74, 0.75)	57.5
First quartile (FS, 0-43.8)	3.8	76.7	15.2 (13.4, 17.0)	0.79 (0.78, 0.80)	55.7
Second quartile (FS, >43.8-51.9)	3.7	82.5	10.2 (9.8, 10.6)	0.80 (0.79, 0.81)	56.1
Third quartile (FS, >51.9-59.3)	3.7	85.0	7.1 (6.0, 8.3)	0.79 (0.78, 0.80)	54.8
Fourth quartile (FS, >59.3-100)	3.9	85.7	3.7 (2.6, 4.7)	0.75 (0.74, 0.76)	56.8

Abbreviations: AUC, area under the ROC curve; FS, functional status; GROC, global rating of change; MCII, minimal clinically important improvement; ROC, receiver operating characteristic; SEM, standard error of measurement.
**Estimate of MCII across the full score range and by quartiles of Neck Functional Status Computerized Adaptive Test scores at admission, based on a GROC cut score of 3 or more (n = 126 026).*
†Median standard error from the computerized adaptive test surveys.
‡Values in parentheses are 95% confidence interval.

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TABLE 6 Functional Staging Model Operational Definitions

Stage (Score Range)	Title	Operational Definition
1 (0-30)	Limited self-care	Exceedingly limited in neck motion, basic self-care tasks, or reaching
2 (>30-40)	Light activity	Able to perform neck motion, basic self-care tasks, or reaching with difficulty
3 (>40-57)	Moderate activity	Able to move light- to medium-weight objects, perform neck motions, or move in bed with minimal to moderate difficulty. Able to perform basic self-care tasks with minimal to no difficulty
4 (>57-74)	High activity	Able to perform high-level activities with minimal to moderate difficulty or neck motions with minimal to no difficulty
5 (>74-100)	Vigorous activity	Able to perform vigorous work/occupation tasks, sports, recreational activities, and heavy household tasks/yard work and able to handle heavy objects overhead with minimal to no difficulty

TABLE 7 Functional Staging Testing Example*

NFS-CAT Item	Patient's Response
Looking up to see a bird	Extreme difficulty or unable to perform
Performing recreational activities that require little effort (eg, card playing, knitting, etc)	Quite a bit of difficulty
Reaching for and pulling a string that controls a light or fan	Quite a bit of difficulty
Placing a can of soup (1 lb) on a shelf overhead	Extreme difficulty or unable to perform
Looking down to see your shoes	Quite a bit of difficulty
Combing or brushing your hair	Moderate difficulty
Performing personal care activities like washing, dressing, or bathing	Extreme difficulty or unable to perform

Abbreviation: NFS-CAT, Neck Functional Status Computerized Adaptive Test.
This table describes an example of patient responses to an actual NFS-CAT survey administered at intake. Physical therapists (n = 10) who participated in the testing phase were asked to identify the functional stage associated with the NFS-CAT items and patient responses described in the table. In this example, the NFS-CAT score was 28, putting the patient in stage 1. Examining these questions and responses, along with the information provided in* **FIGURE 1, *demonstrates how the expected stage could be identified.*

TABLE 8 Functional Staging Change From Admission to Discharge*

	Functional Stage at Discharge					
Functional Stage at Admission	1	2	3	4	5	Total
1	0.4	0.7	1.2	0.9	0.3	3.5
2	0.3	1.6	5.4	4.1	1.0	12.4
3	0.1	1.3	16.2	24.0	7.2	48.8
4	0.0	0.1	2.8	18.4	11.0	32.3
5	0.0	0.0	0.0	0.7	2.2	2.9
Total	0.8	3.7	25.6	48.1	21.7	100.0

**Values are percent and represent the rate of functional staging change from admission to discharge (n = 169 039).*

The ability to categorize each patient within a clinically defined functional stage provides additional useful information regarding a patient's current functional or physical abilities. For instance, a patient classified into stage 1 at intake would report extreme difficulty or inability to perform most neck motions, basic self-care, and reaching tasks such as bathing or combing one's hair. The study results also demonstrated the clinical utility of the NFS-CAT's functional staging model to improve interpretation of change scores during the patient's episode of care. For example, consider a patient with an admission score of 35 and a discharge score of 70. The functional staging model suggests improvement from stage 2 at admission to stage 4 at discharge (**TABLE 6**). This change is also considered clinically meaningful, exceeding the MCII cut point of 15.2 points for patients with admission scores in the lower quartile (**TABLE 5**).

The comparison of patients with incomplete and complete outcomes data (**TABLE 2**) did not support systematic patient selection bias, with no statistically significant differences in admission NFS-CAT scores, the strongest predictor of outcome scores. Some statistically significant differences were interpreted as being related to the large sample size. Examples included the average number of comorbidities (5.257 versus 5.296) and the percent of patients having no related surgeries (87.6% versus 87.9%). Other significant differences were found, but the direction of potential bias was inconsistent, some favoring the group with complete outcomes data and others favoring the group with incomplete data. For example, patients with complete outcomes data, compared to those with incomplete outcomes data, were 3 years older and therefore expected to have worse outcomes, not supporting bias. However, those same patients also had a higher rate of Medicare Part B coverage for those aged 65 years or older, which has been associated with better outcomes.[10] Also, patients with complete

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data had slightly more acute pain, exercised more, and used less medication at intake, characteristics associated with better outcomes, leaving the possibility that some patient selection bias might have existed.

This study had some limitations. First, though we found no consistent evidence of patient selection bias, some nonrandomness of missing outcomes data might still exist. Second, the anchor-based estimates of important change were calculated using a GROC item worded to identify the level of change rather than important change.[33] As reported previously by Stratford and Riddle,[59] assessing the amount of change in an outcome measure is not the same as assessing the importance of change.[59] Additional studies on the impact of different GROC items, or a triangulation of multiple anchor-based estimates of important change, on estimates of MCII are warranted. Finally, using internal consistency estimates of reliability, as done here, is likely to underestimate test-retest reliability, as it ignores random fluctuations owing to time.[39] Identifying stable patients by their GROC score could serve as a selection criterion for test-retest studies to assess point estimates of reliability over repeated measures.

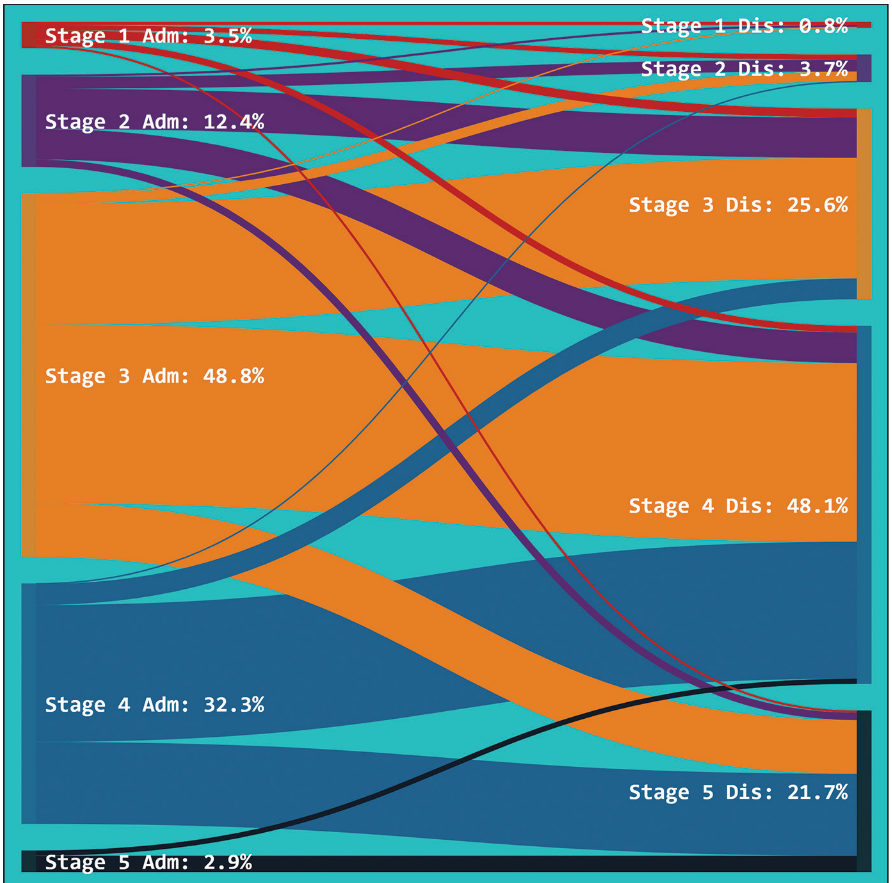

FIGURE 3. Sankey diagram of functional staging change between admission and discharge (n = 169 039). Higher stages represent better functional status. The diagram illustrates the percentage of functional staging change during treatment. For example, most patients starting at stage 2 improved to stage 3, followed by stages 4 and 5, with a negligible percentage deteriorating to stage 1. Large amounts of change between functional stages support the responsiveness of the functional staging model to functional status change during treatment. Percentages in the diagram at admission and discharge sum to 99.9% due to the exclusion of 4 categories with rates less than 0.1% (0% for stage 4 to 1, stage 5 to 1, stage 5 to 2, and stage 5 to 3). Abbreviations: Adm, admission; Dis, discharge.

CONCLUSION

This study demonstrated how the NFS-CAT PROM can be interpreted to assist clinicians and patients with neck impairments during outpatient rehabilitation. The NFS-CAT is used routinely in outpatient rehabilitation clinics across the United States and Israel, attesting to its efficiency and usability. Our results should improve the clinical interpretation of the NFS-CAT and stimulate future studies, for the benefit of patients. ◉

KEY POINTS

FINDINGS: This study provided a set of estimates useful to interpret scores derived from the Neck Functional Status Computerized Adaptive Test, including reliability of point estimates and improvement scores, cut scores of minimal clinically important improvement, and a physical functioning staging model.

IMPLICATIONS: The Neck Functional Status Computerized Adaptive Test can be interpreted in clinically useful ways to assist clinicians and patients in clinical decision making during an episode of care for patients treated in physical therapy for neck impairments.

CAUTION: Although the patient sample used in this study was large and diverse, results might not be valid for patients treated in different clinical settings, or different cultural or geographical environments.

ACKNOWLEDGMENTS: *We thank the thousands of rehabilitation therapists and their facilities across the United States engaged in ongoing outcomes data collection for the benefit of their patients. We also thank the therapists who participated in the functional staging model testing for their assistance.*

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Hip Biomechanics During a Single-Leg Squat: 5 Key Differences Between People With Femoroacetabular Impingement Syndrome and Those Without Hip Pain

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Hip biomechanics during tasks such as walking, squatting, and stair climbing are altered in people with femoroacetabular impingement (FAI) syndrome.[2,9,10,15,19,24-26,35,36] However, most of these studies have investigated gait,[12,19,21,24,35,36] which is a task that does not require hip positions expected to reproduce symptomatic impingement in people with FAI syndrome. Gait does not require near-end ranges of hip flexion, internal rotation, and adduction motions.[12,19,21,24,35] Therefore, squat tasks might be more appropriate to assess for symptomatic impingement in people with FAI syndrome.[5,11,33]

BACKGROUND: The hip joint biomechanics of people with femoroacetabular impingement (FAI) syndrome are different from those of healthy people during a double-leg squat. However, information on biomechanics during a single-leg squat is limited.

OBJECTIVES: To compare hip joint biomechanics between people with FAI syndrome and people without hip pain during double-leg and single-leg squats.

METHODS: Fourteen people with FAI syndrome (cam, n = 7; pincer, n = 1; mixed, n = 6) and 14 people without hip pain participated in this cross-sectional, case-control, laboratory-based study. Three-dimensional biomechanics data were collected while all participants performed a double-leg and a single-leg squat. Two-way mixed-model analyses of variance were used to assess group-by-task interactions for hip joint angles, thigh and pelvis segment angles, hip joint internal moments, and squat performance variables. Post hoc analyses for all variables with a significant group-by-task interaction were performed to identify between-group differences for each task.

RESULTS: There were significant group-by-task interactions for peak hip joint (P = .014, η^2 = 0.211) and thigh segment (P = .009, η^2 = 0.233) adduction angles, and for peak hip joint abduction (P = .002, η^2 = 0.308) and extension (P = .016, η^2 = 0.203) internal moments. There were no significant group-by-task interactions for squat performance variables.

CONCLUSION: Biomechanical differences at the hip between people with FAI syndrome and those without hip pain were exaggerated during a single-leg squat compared to a double-leg squat task.

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KEY WORDS: *double-leg squat, hip biomechanics, hip joint, single-leg squat*

The kinematic differences during a double-leg squat in people with FAI syndrome compared to those without hip pain include reduced sagittal plane pelvic range of motion,[25] reduced peak hip internal rotation,[2] and greater anterior pelvic tilt at peak hip flexion.[2] Some people with FAI syndrome may have altered hip joint internal moments, such as smaller average hip extension[2] and peak internal rotation moments,[10,24] compared to healthy controls. Although a double-leg squat is useful in bringing out pelvic and hip motion compensations in patients with FAI syndrome, the bilateral nature of this task may make it less challenging for a young or active patient. A single-leg squat task is inherently more challenging and could accentuate movement compensations. People with FAI syndrome have kinematic and kinetic alterations during a unilateral step-up task and a step-down task, including slower stair ascent, greater peak trunk flexion angles, greater peak hip external rotation joint moments,[15] and greater hip flexion and anterior pelvic tilt.[27]

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Understanding how people with FAI syndrome perform different squat tasks could help the clinician evaluate movement patterns in FAI syndrome. The purpose of this study was to determine differences in hip joint biomechanics between people with FAI syndrome and people without hip pain during double-leg and single-leg squat tasks. We hypothesized that hip joint biomechanics between people with FAI syndrome and people without hip pain would be different, and that the biomechanical differences would be greater during a single-leg squat task than during a double-leg squat task.

METHODS

We used a cross-sectional, case-control design with 2 independent variables. The first independent variable was group, with 2 levels: people with FAI syndrome and people without hip pain. The second independent variable was task, with 2 levels: double-leg squat and single-leg squat.

Participants

Previous studies have reported effect sizes on the order of 0.3 for biomechanical differences between people with FAI syndrome and people without hip pain during various functional tasks.[2,22] Thus, to have a 90% chance of detecting an effect that accounted for 30% of the variance between the groups for the squat tasks at an a priori alpha level of .05, 13 participants per group were needed for a mixed-model statistical design.[20] We enrolled 14 people with FAI syndrome and 14 people without hip pain in this study (**TABLE 1**). All participants were between 14 and 40 years of age (mean ± SD age, 24.4 ± 6.4 years) at the time of the study and signed a written informed-consent or assent form prior to participation in this study. The informed-consent/assent form and study protocol were approved and in compliance with all human subject protections set forth by the Institutional Review Board of Marquette University.

All participants with FAI syndrome were diagnosed by an orthopaedic surgeon specializing in young adult hip preservation. Diagnosis of FAI syndrome required the following criteria: (1) hip pain for at least 3 months; (2) a positive anterior impingement (flexion, adduction, internal rotation [FADIR]) test; (3) radiographic evidence of FAI, defined by an alpha angle greater than 55° (cam morphology), center-edge angle greater than 40° (pincer morphology), or confirmed crossover sign (pincer morphology); (4) a Tönnis grade of 1 or less on a standard radiograph; (5) magnetic resonance imaging with no evidence of diffuse articular cartilage degeneration; and (6) positive response to an intra-articular anesthetic injection, which was defined as temporary pain relief during impingement testing immediately following the injection. We excluded participants if they (1) reported low back or lower extremity injury within the last 6 months, (2) had a history of hip fracture or dislocation, (3) had a previous diagnosis of any developmental hip conditions such as acetabular dysplasia, or (4) had any systemic disorders that limited activities of daily living.

We recruited a convenience sample of people without hip pain from a general university population to serve as a control group. We matched the groups for sex, body mass, and height. Diagnosis of FAI syndrome had to include "a triad of symptoms, clinical signs, and imaging findings."[14] A licensed physical therapist screened all controls using passive range of hip motion and a physical examination (anterior impingement [FADIR] test; flexion, abduction, external rotation [FABER] test; log-roll test; and dial test[4,5,33]) to determine whether symptoms and clinical signs were present. Limited hip flexion was less than 85°, and limited internal rotation at 90° of hip flexion was less than 10°. We excluded participants if any examination technique elicited anterior groin or lateral hip pain or met the predetermined cutoffs for range-of-motion limitation. One person without hip pain failed the screening examination secondary to pain during the FADIR test and the flexion, abduction, external rotation test.

TABLE 1 Demographic Information for People With FAI Syndrome and People Without Hip Pain*

	FAI Syndrome (n = 14)	No Hip Pain (n = 14)	*P* Value
Sex, n			
Male	7	7	
Female	7	7	
Age, y	28 ± 7	21 ± 1	<.001
Height, m	1.7 ± 1.1	1.7 ± 1.2	.87
Weight, kg	76.3 ± 18.2	71.3 ± 15.5	.44

Abbreviation: FAI, femoroacetabular impingement.
**Values are mean ± SD unless otherwise indicated.*

Data Acquisition

We used a 14-camera motion-analysis system (Vicon; Oxford Metrics, Yarnton, UK) to sample position data at 100 Hz. Position data were recorded from 45 retroreflective markers, including markers attached to individual anatomical landmarks (23 markers total) and 3 sets of rigid marker clusters attached to the bilateral thigh, shank, and foot segments (22 markers total). Each thigh and shank cluster contained 4 markers and each heel cluster contained 3 markers. Individual markers were attached to the following anatomical landmarks: C7 spinous process, T10 spinous process, sternal notch, bilateral posterior superior iliac spines, bilateral iliac crests, bilateral anterior superior iliac spines, bilateral

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greater trochanters, bilateral medial and lateral knee joint lines, bilateral medial and lateral malleoli, bilateral fifth metatarsal heads, and bilateral first metatarsal heads. All markers were attached by the same investigator for all participants.

A static standing trial was performed with all markers to define segment parameters and estimate joint center locations. Participants stood in a self-selected pelvic posture, with the feet positioned at shoulder-width distance, the toes pointed forward, and the arms raised to approximately 90° of shoulder abduction, with the elbows in full extension. Three-dimensional ground reaction force data were sampled at 1000 Hz with 2 in-ground force plates (Advanced Mechanical Technology, Inc, Watertown, MA).

Double-Leg and Single-Leg Squat Tasks

All squats were performed at self-selected speeds to be more representative of movement evaluations in the clinical setting. We instructed participants to "squat as low as possible while keeping your feet/foot firmly in contact with the force plate(s) at all times." We did not use a depth target; instead, we emphasized a self-selected movement strategy to account for individual differences in hip range of motion. Prior to data collection, a task familiarization session was provided, which included an example squat demonstration by the study staff. Participants completed 3 practice trials of each squat task prior to data collection.

For the double-leg squat task, participants stood with each foot on a force plate at shoulder-width distance and the toes pointing forward (**FIGURE 1**). For the single-leg squat task, participants stood on a force plate with the stance-limb toes pointing forward and with the nonstance limb held so that the knee was flexed to a comfortable position, with the nonstance thigh behind the squat leg during the movement (**FIGURE 2**). During both squat tasks, participants raised their arms to shoulder height, with their fingertips pointing forward and palms facing the floor.

Participants performed 5 successful double-leg and single-leg squats to maximal depth. A successful trial was a squat where the participant's feet/foot remained in contact with the force plate(s) throughout the movement, stable balance was

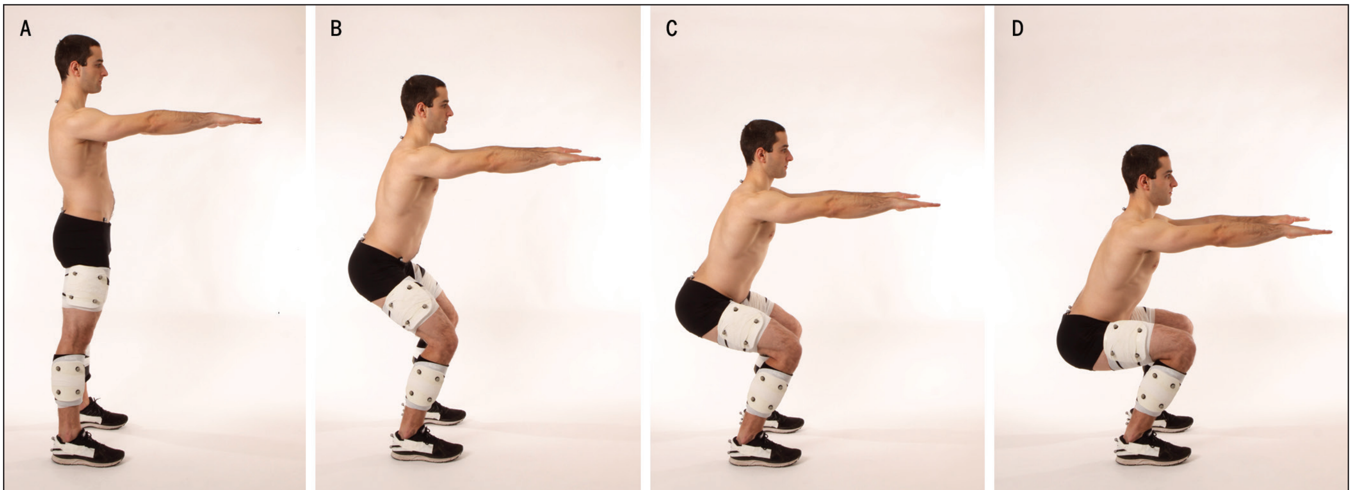

FIGURE 1. The double-leg squat task was performed by all participants as shown.

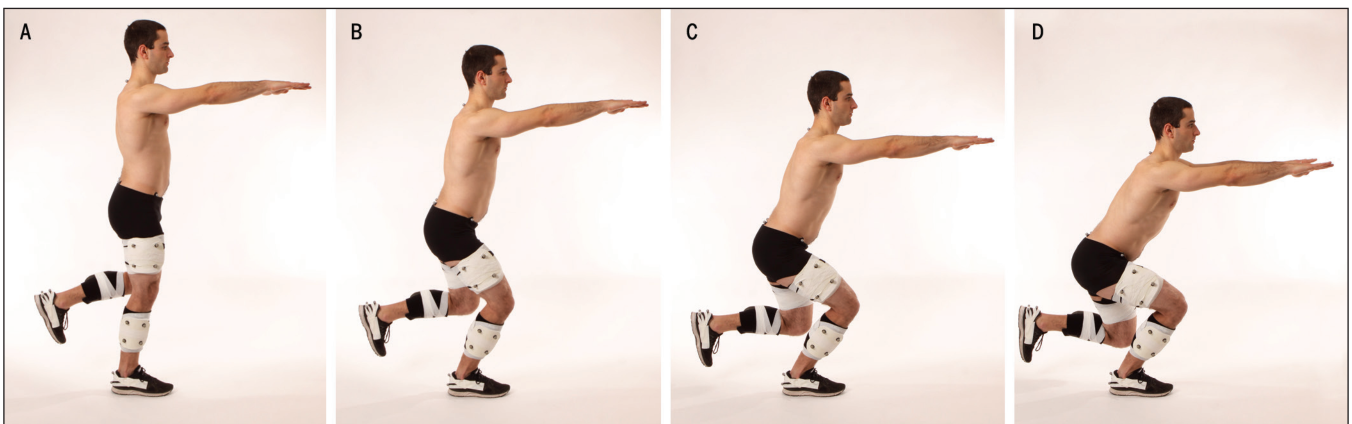

FIGURE 2. The single-leg squat task was performed by all participants as shown.

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maintained without shifting the stance foot/feet on the plate(s), and the nonstance foot (single-leg squat) did not touch the ground. There was a 30-second break between each squat, and no more than 6 trials were collected per leg.

Data Processing and Analysis

Kinematic and kinetic data were processed with Visual3D software (C-Motion, Inc, Germantown, MD). Data were filtered with a fourth-order, low-pass Butterworth filter at a cutoff frequency of 6 Hz. A hybrid link segment model was built using the CODA pelvis (Charnwood Dynamics Ltd, Rothley, UK). Hip joint angles were defined as the angle between the thigh and pelvis segments, using an *x-y-z* (mediolateral, anteroposterior, longitudinal) Cardan sequence of rotations, which are equivalent to flexion/extension, abduction/adduction, and internal/external rotation.[7] All pelvis and thigh segment angles are reported with respect to the laboratory coordinate system. We used an inverse dynamics approach to calculate net joint moments. All joint moments are reported as internal moments and were normalized to body mass (Newton meters per kilogram).

We extracted peak biomechanical variables from the non–time-normalized kinematic and kinetic waveforms prior to normalizing the data to 100 data points. We calculated 5-trial averages for each peak biomechanical variable. Because cam and/or pincer morphology is often bilateral, we analyzed data from the involved hip of the FAI syndrome group and the matched leg of the control group.[1,23]

During a double-leg squat, the hip joint moves into the direction of abduction,[2,24] whereas during a single-leg squat the hip moves toward the direction of adduction.[13] Similarly, during a double-leg squat, the predominant peak frontal plane moment is in the direction of adduction,[2,24] whereas during a single-leg squat this peak moment is in the opposite direction (abduction). Therefore, we analyzed both peak abduction and adduction angles and moments to account for the different frontal plane kinematics and kinetics that occur during each type of squat task.

We used the biomechanical model's virtual center of mass (CM)—calculated from the estimated masses of all segments included in the model (the bilateral thighs, shanks, and feet, as well as the pelvis and trunk)—to determine the squat cycle length and to calculate the squat performance variables. The start and end points of the squat cycle were defined as when the CM vertical position was 3 SD away from the quiet stance CM vertical position. Squat depth was the change in CM position from quiet stance to the minimum vertical position during the squat cycle.

We evaluated (1) descent phase, from the beginning of the squat cycle to the minimum vertical CM position, and (2) ascent phase, from the minimum vertical CM position to the end of the squat cycle. The first-time derivative of CM position was calculated to determine CM velocity. The average CM velocity was calculated for each phase of the squat cycle during each trial. We calculated the 5-trial average for each squat performance variable.

Five people without hip pain performed 2 motion-analysis testing sessions, 7 days apart. We used these data to assess test-retest reliability for peak kinematic and kinetic variables, using intraclass correlation coefficient (ICC) models. The average $ICC_{3,3}$ for peak hip joint kinematics was 0.75, with a standard error of measurement of 2.15°, and the average $ICC_{3,3}$ for hip joint kinetics was 0.78, with a standard error of measurement of 0.08 Nm/kg.

Patient-Reported Outcomes

Participants in the FAI syndrome group completed the Hip Outcome Score activities of daily living subscale and International Hip Outcome Tool-33 to assess hip function and quality of life. Both tools are reliable and valid measures of self-reported physical function and quality of life in young people with nonarthritic hip pain.[29,30]

Statistical Analysis

We inspected box plots for all dependent variables to evaluate the presence of outliers. We used the Shapiro-Wilk test of normality to ensure all data were normally distributed, Levene's test to ensure homogeneity of variance, and Box's test to evaluate the equality of covariance matrices, as necessary, for repeated-measures analysis.

We used 2-tailed independent-samples *t* tests to assess between-group differences in age, body mass, and height. For group-by-task interactions, we used 2-way mixed-model analyses of variance for all dependent variables. For any variable with a significant group-by-task interaction, follow-up post hoc analyses, consisting of a 2-tailed independent-samples *t* test, were performed to evaluate between-group differences for each level of task. For dependent variables without a significant group-by-task interaction, main effects for group were reported using Bonferroni corrections for multiple comparisons.

The dependent biomechanical variables of interest were peak hip joint kinematics, peak thigh segment kinematics, peak pelvis segment kinematics, peak hip joint kinetics, and squat performance variables (**TABLE 2**). Effect sizes for the 2-way mixed-model analyses of variance were evaluated with the partial eta-square statistic and were interpreted as small (approximately 0.01), medium (approximately 0.06), and large (approximately 0.14).[34] Cohen's *d* was used to estimate effect sizes for all univariate post hoc analyses and was defined as small (approximately 0.2), medium (approximately 0.5), and large (approximately 0.8), as suggested by Cohen.[6] An a priori alpha level of .05 was used as the threshold for statistical significance. All statistical testing was performed using SPSS Version 22 (IBM Corporation, Armonk, NY).

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RESULTS

There were no differences in height or body weight (**TABLE 1**). People without hip pain were younger than those with FAI syndrome (**TABLE 1**). Seven people with FAI syndrome had cam morphology, 1 person had pincer morphology, and 6 people had mixed morphology (ie, combined cam and pincer morphology) (**TABLE 3**). People with FAI syndrome had moderate functional limitations (**TABLE 3**).[32]

Hip Kinematics

There was a significant group-by-task interaction for peak hip joint adduction angle ($F_{1,26}$ = 6.958, P = .014, η^2 = 0.211) (**TABLE 4**). During the single-leg squat task, people with FAI syndrome had 6° less peak hip joint adduction than people without hip pain (P = .03, d = 0.87). During the double-leg squat task, peak hip joint adduction angles were similar between the FAI syndrome group and people without hip pain (P = .68, d = 0.16) (**FIGURE 3**).

There was a significant group-by-task interaction for peak thigh segment adduction angle ($F_{1,26}$ = 7.878, P = .009, η^2 = 0.233) (**TABLE 4**). People with FAI syndrome had 4° less peak thigh segment adduction during the single-leg squat task when compared to people without hip pain (P = .02, d = 0.92) (**FIGURE 4**). There were no significant differences between the FAI syndrome group and people without hip pain for peak thigh segment adduction during the double-leg squat task (P = .11, d = 0.63) (**FIGURE 4**).

There was a significant main effect of group for peak thigh segment abduction angle (P = .017, η^2 = 0.200). There were no other main effects of group (**TABLE 4**).

Hip Kinetics

There was a significant group-by-task interaction for peak hip joint abduction internal moment ($F_{1,26}$ = 11.591, P = .002, η^2 = 0.308) (**TABLE 5**). On average, peak hip joint abduction internal moments in people with FAI syndrome were 30% of body mass smaller than in people without hip pain during the single-leg squat task (P = .01, d = 1.04). There were no differences in peak hip abduction internal moments during the double-leg squat task (P = .08, d = 0.71) (**FIGURE 5**).

TABLE 2 Study Design, Including the Independent Variables (Group and Task) and All Dependent Kinematic, Kinetic, and Squat Performance Variables of Interest*

Variable	Measurement
Kinematic, deg	• Peak hip joint flexion • Peak hip joint adduction • Peak hip joint abduction • Peak hip joint internal rotation • Peak thigh segment flexion • Peak thigh segment adduction • Peak thigh segment abduction • Peak anterior pelvic tilt • Peak lateral pelvic tilt†
Kinetic, Nm/kg	• Peak hip extension moment • Peak hip abduction moment • Peak hip adduction moment • Peak hip external rotation moment
Squat performance	• Center-of-mass depth, m • Center-of-mass descent velocity, m/s • Center-of-mass ascent velocity, m/s • Squat cycle duration, s

There were 2 tasks, the double-leg squat and single-leg squat, and 2 groups, those without hip pain and those with femoroacetabular impingement syndrome.
†*Refers to contralateral pelvic drop.*

TABLE 3 Patient-Reported Outcome Scores and Radiographic Measurements for People With Femoroacetabular Impingement Syndrome*

Measure	Value
HOS-ADL, %	70.4 ± 13.8
iHOT-33, mm	45.0 ± 17.5
Alpha angle, deg	63.5 ± 8.8
Lateral center-edge angle, deg	39.0 ± 6.5
Crossover sign (positive case), n	3

Abbreviations: HOS-ADL, Hip Outcome Score activities of daily living subscale; iHOT-33, International Hip Outcome Tool-33.
**Values are mean ± SD unless otherwise indicated.*

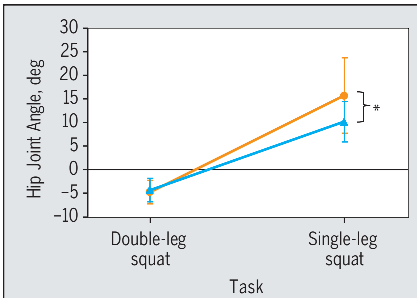

FIGURE 3. Peak hip joint adduction angles during the double-leg and single-leg squat tasks in people with femoroacetabular impingement syndrome (blue) and people without hip pain (orange). Positive values represent adduction and negative values represent abduction. *Significant (P<.05) post hoc difference of group for the single-leg squat task.

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There was a significant group-by-task interaction for peak hip joint extension internal moments ($F_{1,26}$ = 6.240, P = .016, η^2 = 0.203). On average, peak hip extension internal moments in people with FAI syndrome were smaller by 70% of body mass during the single-leg squat task (P = .004, d = 1.27) and by 20% of body mass during the double-leg squat task (P = .03, d = 1.00) when compared to people without hip pain (**FIGURE 6**). There were no other group-by-task interactions or main effects of group (**TABLE 5**).

Squat Performance

There were no group-by-task interactions for squat depth, squat cycle duration, and squat descent and ascent velocity (**TABLE 6**). People with FAI syndrome had a longer squat cycle duration (P = .031, η^2 = 0.167), slower squat descent velocity (P = .008, η^2 = 0.244), and slower squat ascent velocity (P = .009, η^2 = 0.237) than people without hip pain. There was no main effect of group for squat depth (P = .24, η^2 = 0.054) (**TABLE 6**).

DISCUSSION

A SINGLE-LEG SQUAT TASK EXAGGERATED movement-pattern differences between people with FAI syndrome and those without hip pain when compared to a double-leg squat task. During a single-leg squat task, people with FAI syndrome squatted more slowly and with less peak hip adduction than people without hip pain. People with FAI syndrome had lower peak hip joint abduction and extension moments than people without hip pain during a single-leg squat task. The clinician might observe that patients with FAI syndrome perform a single-leg squat slowly to avoid medial collapse of the thigh into hip adduction as the hip approaches near-end-range flexion. This movement strategy may be developed to avoid symptomatic bony impingement and to limit joint load demands during single-leg squat tasks. The clinician might consider routinely assessing single-leg squat performance in people with FAI syndrome.

Five Key Biomechanical Differences in Single-Leg Squat Performance Between People With FAI Syndrome and Those Without Hip Pain

In this section, we outline 5 main biomechanical differences in single-leg squat performance in participants with FAI syndrome. One should consider the kinematic findings in the context of the symptomatic impingement position in people with FAI syndrome, which involves combined hip flexion, adduction, and internal rotation. Although clinicians can only assess movement patterns and not directly observe internal joint moments, one may consider how the observed hip movement patterns may affect the hip internal joint moments.

Smaller Peak Hip Joint and Thigh Segment Adduction Angles Although greater hip adduction motion during a single-leg squat is part of an abnormal movement pattern in people with chronic hip pain,[16,17] perhaps people with hip pain specific to FAI syndrome adopt a different movement strategy. People with FAI syndrome did not collapse medially into hip adduction during the single-leg squat. The FAI syndrome group had 9° less peak hip flexion during a single-leg squat but only 2° less peak hip flexion during the double-leg squat when compared to people without hip pain. The combination of hip flexion and adduction motion during a single-leg squat could reproduce symptomatic bony impingement in people with FAI syndrome. These reduced joint angles in people with FAI syndrome suggest a movement strategy to avoid reproducing hip pain secondary to bony impingement that may occur with combined flexion and adduction.[5,31]

Smaller Peak Hip Abduction Joint Moments Internal joint moments mostly reflect which muscle groups are active during a task. Dynamic tasks that require single-limb support often result in large hip joint contact forces, with the hip muscles being the primary contributor to these forces.[3,8,18,37] Therefore, during a single-leg squat, a large peak hip abduction internal

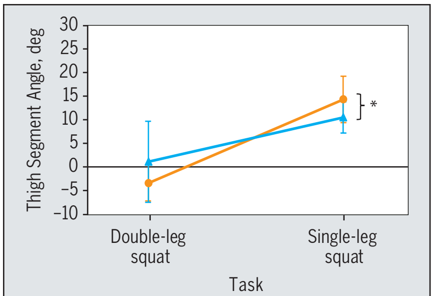

FIGURE 4. Peak thigh segment adduction angles during the double-leg and single-leg squat tasks in people with femoroacetabular impingement syndrome (blue) and people without hip pain (orange). Positive values represent adduction and negative values represent abduction. *Significant (P<.05) post hoc difference of group for the single-leg squat task.

FIGURE 5. Peak hip abduction internal joint moments during the double-leg and single-leg squat tasks in people with femoroacetabular impingement syndrome (blue) and people without hip pain (orange). *Significant (P<.05) post hoc difference of group for the single-leg squat task.

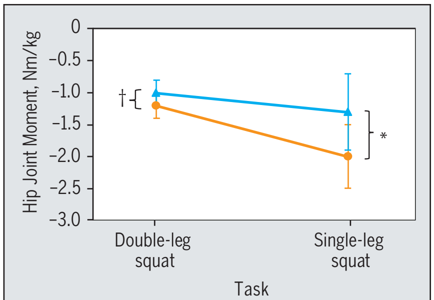

FIGURE 6. Peak hip extension internal joint moments during the double-leg and single-leg squat tasks in people with femoroacetabular impingement syndrome (blue) and people without hip pain (orange). *Significant (P<.05) post hoc difference of group for the single-leg squat task. †Significant (P<.05) post hoc difference of group for the double-leg squat task.

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moment would represent considerable activity from the hip abductor muscle group.[37] In this context, the smaller peak hip abduction moments in people with FAI syndrome may signify a movement strategy to limit hip abductor muscle activity and, potentially, high joint contact forces during this dynamic single-leg task.

Smaller Peak Hip Extension Joint Moments The between-group differences for peak hip extension moments were most pronounced during the single-leg squat. Our double-leg squat extension moment findings are consistent with Bagwell and colleagues,[2] who found that people with FAI syndrome demonstrate smaller average hip extension moments during a double-leg squat compared to healthy controls. Because both types of squats would require hip extensor muscle activity, with greater activation required during a single-leg squat, these findings may also represent a movement strategy to limit hip extensor muscle activity and, potentially, high joint contact forces.

Slower CM Velocity During Squatting Slower CM velocities during the squat cycle might explain the lower peak hip joint abduction and extension internal moments in people with FAI syndrome, and reflect a global squat performance adaptation. This may be a strategy to reduce the load demands across the hip during squat tasks. Both types of squat tasks require eccentric muscle activation to halt momentum of the CM prior to the ascent phase. During a double-leg squat, the hip adductor muscles act eccentrically to control hip joint abduction as the CM descends (**APPENDIX FIGURE 1**, available at www.jospt.org). Similarly, during a single-leg squat, the hip abductor muscles

TABLE 4 PEAK KINEMATIC DATA DURING THE DOUBLE-LEG AND SINGLE-LEG SQUAT TASKS IN PEOPLE WITH FAI SYNDROME AND PEOPLE WITHOUT HIP PAIN

	FAI Syndrome*		No Hip Pain*		*P* Value	
	DLS	SLS	DLS	SLS	Group	Group by Task
Hip joint angles						
Peak flexion	104.0 ± 5.8	85.7 ± 10.2	106.1 ± 11.8	94.7 ± 13.1	.14	.05
Peak adduction	–4.3 ± 2.5	10.2 ± 4.3	–4.7 ± 2.5	15.8 ± 8.0	...	.01†
Peak abduction	–13.9 ± 5.1	1.0 ± 2.6	–16.5 ± 6.8	3.2 ± 5.6	.86	.14
Peak internal rotation	9.2 ± 8.4	4.6 ± 8.2	12.7 ± 7.5	7.0 ± 6.2	.17	.79
Segment angles						
Peak thigh flexion	80.4 ± 11.0	43.6 ± 8.5	85.3 ± 20.8	55.4 ± 12.8	.09	.14
Peak anterior pelvic tilt	33.4 ± 6.1	40.4 ± 8.3	33.4 ± 7.8	39.0 ± 7.9	.78	.65
Peak thigh adduction	0.9 ± 8.6	10.3 ± 3.3	–5.1 ± 3.5	14.1 ± 4.9	...	.01†
Peak thigh abduction	–9.2 ± 9.8	4.9 ± 2.7	–14.4 ± 6.0	4.4 ± 2.8	.02‡	.06
Peak lateral pelvic tilt	–2.8 ± 1.6	–7.9 ± 4.6	–2.9 ± 3.5	–10.7 ± 2.5	.15	.07

Abbreviations: DLS, double-leg squat; FAI, femoroacetabular impingement; SLS, single-leg squat.
**Values are mean ± SD degrees. Positive angles represent flexion, adduction, internal rotation, and anterior pelvic tilt. Negative angles represent extension, abduction, external rotation, and contralateral pelvic drop.*
†Statistically significant interaction of group by task.
‡Main effect of group.

TABLE 5 PEAK KINETIC DATA DURING THE DOUBLE-LEG AND SINGLE-LEG SQUAT TASKS IN PEOPLE WITH FAI SYNDROME AND PEOPLE WITHOUT HIP PAIN

	FAI Syndrome*		No Hip Pain*		*P* Value	
	DLS	SLS	DLS	SLS	Group	Group by Task
Internal hip joint moments						
Peak extension	–1.0 ± 0.2	–1.3 ± 0.6	–1.2 ± 0.2	–2.0 ± 0.5	...	.02†
Peak adduction	0.4 ± 0.2	–0.5 ± 0.2	0.6 ± 0.2	–0.5 ± 0.1	.21	.06
Peak abduction	–0.1 ± 0.1	–0.8 ± 0.3	–0.1 ± 0.1	–1.1 ± 0.3	...	<.01†
Peak external rotation	–0.2 ± 0.1	–0.1 ± 0.2	–0.1 ± 0.1	–0.5 ± 0.1	.64	.40

Abbreviations: DLS, double-leg squat; FAI, femoroacetabular impingement; SLS, single-leg squat.
**Values are mean ± SD Newton meters per kilogram. Positive moments represent flexion, adduction, and internal rotation. Negative moments represent extension, abduction, and external rotation.*
†Statistically significant interaction of group by task.

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act eccentrically to control hip joint adduction as the CM descends (**APPENDIX FIGURE 2**). In the sagittal plane, during the descent phase of both the double-leg and single-leg squat tasks, the hip extensor muscles act eccentrically (**APPENDIX FIGURES 3** and **4**). Therefore, slowing the movement of the CM and lengthening the duration of the squat cycle could result in lower net internal joint moments, allowing the movement of the CM to be controlled with less force at the hip.

Limitations

We cannot be certain that participants without hip pain did not have cam and/or pincer morphology because we did not image their hips.[14] However, the absence of clinical signs and symptoms, such as hip pain, reduced range of motion, and a positive impingement test, rules out FAI syndrome. The groups were matched for height and weight but not for age. Age could influence squat velocity. However, the average age of both groups was between 20 and 30 years, and squat mechanics are unlikely to be tangibly affected by this difference. We did not account for sex differences in the sample-size calculation.[13]

Inclusion in our study required a positive response to an intra-articular injection and positive magnetic resonance imaging and radiographic evidence of FAI syndrome to ensure that hip symptoms had an intra-articular origin. Although the heterogeneity of the sample does represent a limitation, we feel that the stringent inclusion criteria strengthen the design and internal validity of the study. Not controlling the trunk position might influence hip joint internal moments, and the biomechanical results could change if trunk position were controlled. However, controlling the trunk position may be difficult across tasks, because this may require participants to adopt an unnatural movement strategy. Controlling trunk position may limit the generalizability of the results for clinical evaluation, which often involves assessing patients who use a self-selected movement strategy. Finally, extracting peak kinematics and kinetics to represent a maximum angle or moment in a particular direction for each task may not have corresponded to the position of maximum flexion combined with adduction and internal rotation.

CONCLUSION

A single-leg squat task exaggerated biomechanical differences at the hip between people with FAI syndrome and people without hip pain when compared to a double-leg squat task. People with FAI syndrome performed squats more slowly than people without hip pain. ◉

KEY POINTS

FINDINGS: Differences in hip joint kinematics and kinetics between people with femoroacetabular impingement syndrome and people without hip pain are exaggerated during a single-leg squat when compared to a double-leg squat.

IMPLICATIONS: Clinicians might consider using a single-leg squat task during movement assessment of people with femoroacetabular impingement syndrome.

CAUTION: It is possible that the biomechanical alterations in squat performance also depend on a person's sex.

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TABLE 6 Squat Performance Variables During the Double-Leg and Single-Leg Squat Tasks in People With FAI Syndrome and People Without Hip Pain

	FAI Syndrome*		No Hip Pain*		*P* Value	
	DLS	SLS	DLS	SLS	Group	Group by Task
CM depth, m	0.46 ± 0.11	0.25 ± 0.08	0.47 ± 0.13	0.32 ± 0.07	.24	.11
CM descent velocity, m/s	−0.28 ± 0.10	−0.17 ± 0.06	−0.39 ± 0.17	−0.26 ± 0.07	.01†	.42
CM ascent velocity, m/s	0.37 ± 0.13	0.24 ± 0.07	0.47 ± 0.16	0.35 ± 0.06	.01†	.79
Squat cycle duration, s	3.13 ± 0.86	2.57 ± 0.77	2.36 ± 0.63	2.25 ± 0.74	.03†	.16

Abbreviations: CM, center of mass; DLS, double-leg squat; FAI, femoroacetabular impingement; SLS, single-leg squat.
**Values are mean ± SD unless otherwise indicated.*
†Main effect of group.

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APPENDIX

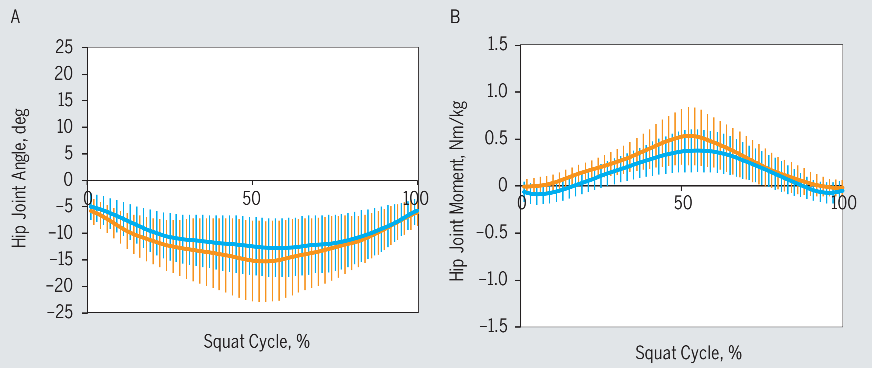

FIGURE 1. (A) Frontal plane hip joint angle and (B) frontal plane hip joint moment during a double-leg squat task in people with femoroacetabular impingement syndrome (blue) and in healthy controls (orange). Positive values indicate adduction and negative values indicate abduction. Values represent the time-normalized group mean and standard deviation.

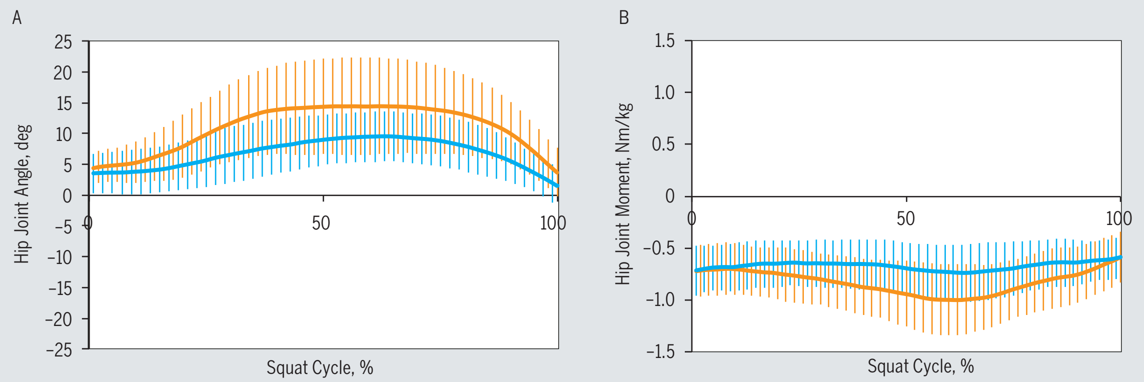

FIGURE 2. (A) Frontal plane hip joint angle and (B) frontal plane hip joint moment during a single-leg squat task in people with femoroacetabular impingement syndrome (blue) and in healthy controls (orange). Positive values indicate adduction and negative values indicate abduction. Values represent the time-normalized group mean and standard deviation.

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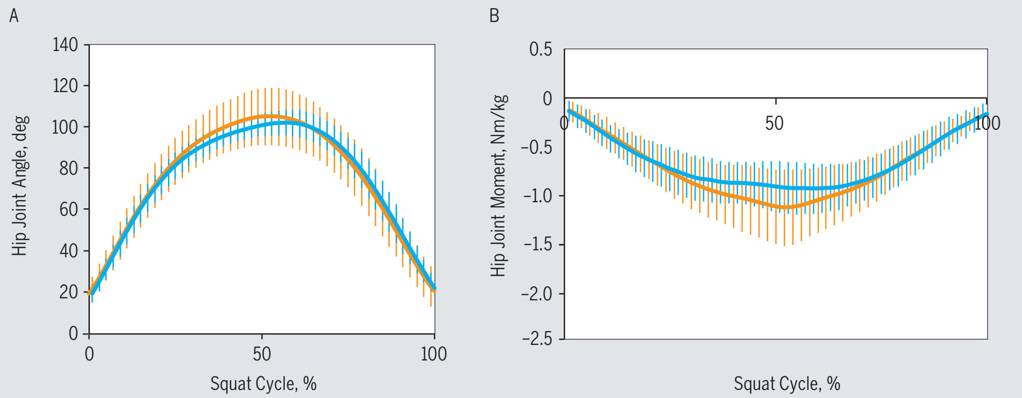

FIGURE 3. (A) Sagittal plane hip joint angle and (B) sagittal plane hip joint moment during a double-leg squat task in people with femoroacetabular impingement syndrome (blue) and in healthy controls (orange). Positive values indicate flexion and negative values indicate extension. Values represent the time-normalized group mean and standard deviation.

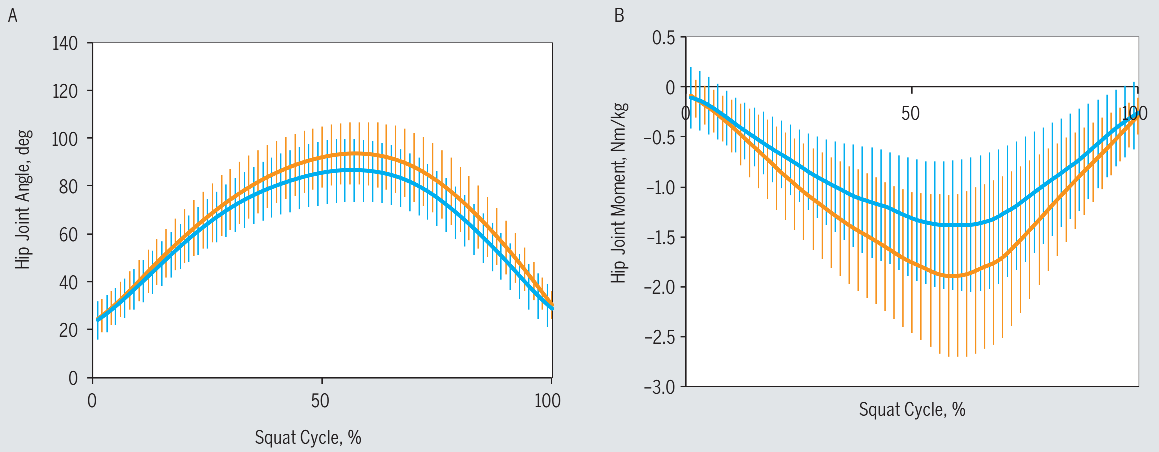

FIGURE 4. (A) Sagittal plane hip joint angle and (B) sagittal plane hip joint moment during a single-leg squat task in people with femoroacetabular impingement syndrome (blue) and in healthy controls (orange). Positive values indicate flexion and negative values indicate extension. Values represent the time-normalized group mean and standard deviation.

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Muscle Function and Muscle Size Differences in People With and Without Plantar Heel Pain: A Systematic Review

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Plantar heel pain, which is also referred to as plantar fasciitis or plantar fasciopathy, is one of the most common musculoskeletal foot conditions.[16] Prevalence estimates range between 4% and 7% in the general and older populations.[8,16] In athletic populations, it has been reported to be one of the most common overuse injuries affecting the foot and ankle, with its prevalence estimated to be up to 8%.[28,31] People with plantar heel pain present with pain at the medial tubercle of the calcaneus on first steps in the morning or after rest, with pain worsening while on their feet as the day progresses.[24] Plantar heel pain has been shown to have detrimental effects on general foot health, activity levels, and social capacity.[17] Furthermore, plantar heel pain has also been associated with clinically important levels of depression.[6]

BACKGROUND: Plantar heel pain is a common condition, but little is known about the relationship between muscle strength and plantar heel pain.

OBJECTIVES: To review the evidence relating to muscle strength in those with and without plantar heel pain.

METHODS: We systematically reviewed the literature by searching key databases. Included studies assessed muscle strength (or endurance or size as proxies) in those with and without plantar heel pain. A modified Downs-Black quality index was used to assess study quality and the Grading of Recommendations Assessment, Development and Evaluation (GRADE) tool was used to evaluate the strength of the evidence. Meta-analysis was performed where possible.

RESULTS: Seven studies met the eligibility criteria. Hallux plantar flexion, lesser toe plantar flexion, ankle dorsiflexion, ankle inversion, and ankle eversion strength values were reduced in those with heel pain compared to those without; however, there was inconsistency in the findings between studies. No difference was found in calf muscle endurance between those with and without plantar heel pain (standardized mean difference, 0.01; 95% confidence interval: –0.56, 0.59). Generally, foot muscle volume was smaller in people with plantar heel pain compared to those without. The quality of individual studies was generally high (score range, 11-16/17 on the modified Downs-Black quality index); however, the GRADE ratings suggest the strength of this evidence to be very low.

CONCLUSION: People with plantar heel pain have reduced strength and volume of the foot muscles, but there is no discernible difference in calf muscle endurance. These findings should be interpreted with respect to the very low GRADE ratings and are likely to change with further research. Accordingly, the role of muscle strength in plantar heel pain is worthy of further investigation.
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KEY WORDS: *foot, muscle performance, muscle physiology, orthoses, podiatry, radiology, strength testing*

One risk factor for plantar heel pain, increased body mass index, has consistently been associated with the condition.[33] However, other risk factors remain unclear, including the relationship of muscle strength to plantar heel pain. For example, a review published in 2016 concluded that there were some muscle strength deficits in people with plantar heel pain, but further research is warranted, as each of the studies reviewed assessed different muscles and used different techniques.[33] If muscle strength is found to be deficient in people with plantar heel pain, this may inform the debate about whether strengthening foot or leg muscles may be of benefit.[27]

It is clear that the role that muscle strength plays in plantar heel pain requires further inquiry and that an up-to-date review of the evidence is warranted. This study aimed to systematically review the evidence relating to muscle strength in those with and without plantar heel pain.

METHODS

This systematic review has been reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[25]

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Search Strategy

A systematic electronic search of the literature was performed on March 10, 2018 using the Ovid (MEDLINE and Embase), EBSCO (CINAHL and SPORTDiscus), and Cochrane Library search engines. Medical subject headings and common terms were explored and used to provide a broad search. Wildcard symbols and truncations were also used. The only limitations or filters applied were "humans" and "18 or over." Reference lists of articles that met inclusion criteria were also hand searched for relevant additional articles. The search strategy is shown in **TABLE 1**.

Inclusion and Exclusion Criteria

Prospective case-control studies, cross-sectional studies, and randomized trials examining muscle strength and/or muscle size in those with plantar heel pain were all considered for inclusion in this review.

Inclusion Criteria Studies were included if they (1) included participants diagnosed with plantar heel pain, plantar fasciopathy, plantar fasciitis, plantar fasciosis, or heel spurs; (2) included muscle function measures of endurance or isometric or dynamic contractions; (3) included muscle size measures assessed by ultrasound or magnetic resonance imaging (MRI) for thickness, cross-sectional area, or volume; and (4) compared a plantar heel pain (case) group to an asymptomatic (control) group without plantar heel pain.

Exclusion Criteria Studies were excluded if they (1) were non–peer-reviewed publications or opinion-based articles (including letters and reviews), (2) were nonhuman studies, (3) were not written or published in English, (4) assessed people with concomitant injuries, or (5) included participants with chronic systemic conditions, such as a connective tissue disease, or degenerative neurological or inflammatory disorders.

Review Process

All titles and abstracts found in the search were imported to EndNote X8 (Clarivate Analytics, Philadelphia, PA) for assessment for inclusion before analysis. Imported studies were first checked for duplicates, and any duplicates were removed. Articles were then assessed based on title and abstract by 2 separate reviewers (J.O. and G.W.) for inclusion in the review. Articles deemed appropriate for inclusion based on title and abstract had the full text obtained and reviewed to assess whether they met the eligibility requirements. Once eligibility was determined, each article was analyzed and its relevant data extracted. A PRISMA flow diagram (**FIGURE 1**) is included to document the phases of the systematic review.[25] All disputes were resolved by consensus between the 2 reviewers.

Quality Assessment

Study-level quality assessment was performed using a modified Downs-Black quality checklist,[7] which is presented in **APPENDIX A** (available at www.jospt.org). The Downs-Black checklist is a valid and reliable quality assessment tool for randomized and nonrandomized studies.[7] Similar reviews have previously used a modified Downs-Black checklist to assess methodological quality.[3,26] Two reviewers (J.O. and G.W.) assessed the studies using the modified checklist, and disputes were resolved by consensus between the 2 reviewers.

This systematic review was not concerned with interventions, so questions from the Downs-Black methodological assessment checklist relevant to intervention studies were not included in quality assessment. The complete Downs-Black quality assessment checklist provides a maximum result of 31 points from 27 questions.[7] However, the modified version provided a maximum score of 17 points from 16 questions. Results were calculated as both a raw score and a percentage of the maximum score.

Outcome-level quality assessment was performed using the Grading of Recom-

TABLE 1 SEARCH STRATEGY

Database	Strategy
Embase and MEDLINE (Ovid)	1. Fasciitis, Plantar/ 2. Heel Spur/ 3. 'plantar heel pain' OR CPHP OR 'plantar fasci*' OR 'heel spur' OR 'calcaneal spur' 4. Muscle Strength Dynamometer/ or Muscle Strength/ 5. Muscle, Skeletal/ 6. 'muscle size' OR 'muscle morph*' OR 'muscle strength' OR 'strength' OR 'intrinsic muscle*' 7. 1 OR 2 OR 3 8. 4 OR 5 OR 6 9. 7 AND 8
CINAHL and SPORTDiscus (EBSCO)	1. MH plantar fasciitis OR MH plantar heel pain OR MH plantar fasciopathy 2. plantar fasci* OR plantar heel pain OR heel spur 3. MH strength OR MH muscle strength 4. strength OR muscle strength OR dynamomet* 5. MH muscle size OR MH muscle morphology 6. muscle size OR muscle morphology 7. 1 OR 2 8. 3 OR 4 OR 5 OR 6 9. 7 AND 8
Cochrane Library	1. MeSH Fasciitis, Plantar exp 2. 'plantar fasci*' or 'plantar heel pain' or 'heel spur' 3. strength or 'muscle strength' 4. morphology or 'muscle size' or 'muscle hypertrophy' 5. 1 OR 2 6. 3 OR 4 7. 5 AND 6

mendations Assessment, Development and Evaluation (GRADE) approach.[9] The criteria that were used to make judgments are presented in **APPENDIX B** (available at www.jospt.org).[11,12] Two reviewers (J.O. and G.W.) assessed the outcomes against each criterion, and disputes were resolved by consensus between the 2 reviewers.

Data Analysis

Data were extracted from all included studies and independently entered into a Microsoft Excel 2018 (Microsoft Corporation, Redmond, WA) spreadsheet by 2 reviewers (J.O. and G.W.). Descriptive and categorical data were also extracted and entered into a Microsoft Excel spreadsheet for comparison and interpretation of findings. The data included participant characteristics (age, sex, weight, body mass index), sample sizes of the studies, and methodological issues such as the type of assessments conducted.

All other data relating to the assessment of muscle strength were continuous in nature (eg, force in Newtons, number of repetitions, cross-sectional area in square millimeters or volume in cubic millimeters). Continuous data (means, mean differences, standard deviations) and *P* values were extracted and then synthesized and analyzed using Review Manager Version 5.8 (The Nordic Cochrane Centre, Copenhagen, Denmark). For all studies included in the meta-analysis except for 1,[21] mean differences or standardized mean differences between participants with and without plantar heel pain, with 95% confidence intervals (CIs) and Cohen's *d* where appropriate, were calculated. Cohen's *d* values were classified as negligible (<0.15), small (0.15 to <0.40), medium (0.40 to <0.75), large (0.75 to <1.10), or very large (≥1.10).[32] To allow visual representation of the data, forest plots were created for all comparisons. Where muscle strength was measured in kilograms, data were converted to force values in Newtons to ensure commonality of the unit of measurement.

A random-effects model of meta-analysis was used for pooling data between 2 studies that measured the single-leg heel raise test to assess calf muscle endurance.[18,30] Heterogeneity between studies in meta-analysis was assessed using the I^2 statistic.

Meta-analysis was not performed on the remaining studies due to heterogeneity between assessment protocols.[1,21,23] Meta-analysis was also not performed on 2 studies that followed similar protocols for assessing muscle size, as one study normalized the results to body weight and the other did not.[4,5]

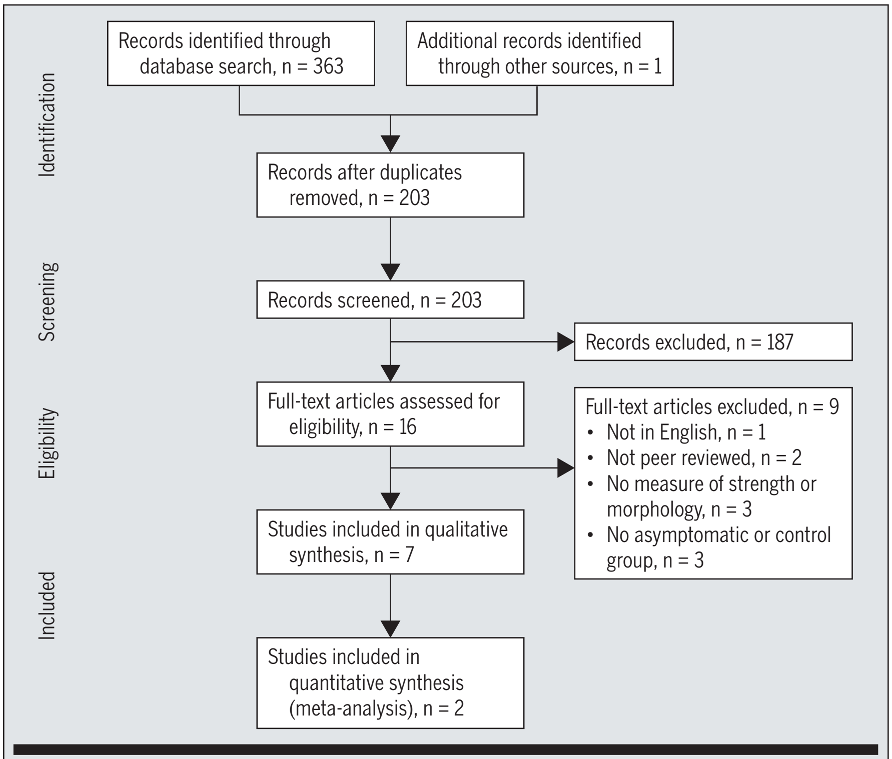

FIGURE 1. Flow diagram of the review process.

RESULTS

Seven studies were deemed appropriate for inclusion, and all were cross-sectional observational studies.[1,4,5,18,21,23,30] Characteristics of the studies (eg, participant characteristics) are presented in **APPENDIX C** (available at www.jospt.org).

Quality Assessment of Included Studies

The quality of included studies was high (**TABLE 2**). Six studies had scores of at least 65%[1,4,5,18,23,30] and 1 study had a score of 35%.[21]

The strength of the evidence for all outcomes was very low (**TABLE 3**). Each outcome was downgraded for limitations and for at least 2 of 3 of the categories of inconsistency, indirectness, or imprecision.

Muscle Strength

Digital Plantar Flexion Two studies assessed hallux plantar flexion strength, with results displayed in **FIGURE 2**.[23,30] No meta-analysis was performed due to heterogeneity in the methods. In both studies, the mean difference (–7.9 N[23] and –15.8 N[30]) indicated that those with plantar heel pain were weaker than those without plantar heel pain. However, the result from the McClinton et al[23] study was not statistically significant. The Cohen's *d* was small (0.14) in the study by McClinton at al[23] and medium (0.45) in the study by Sullivan et al.[30]

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Three studies assessed lesser toe plantar flexion strength, with results displayed in **FIGURE 2**.[1,23,30] No meta-analysis was performed due to heterogeneity in the methods. In all studies, the mean differences (–38.0 N,[1] –5.9 N,[23] and –12.8 N[30]) indicated that those with plantar heel pain were weaker than those without plantar heel pain. However, results from McClinton et al[23] were not statistically significant. The Cohen's *d* was large (0.76) in the study by Allen and Gross,[1] negligible (0.13) in the study by McClinton et al,[23] and medium (0.73) for Sullivan et al.[30]

Ankle Dorsiflexion, Inversion, and Eversion One study assessed ankle dorsiflexion, ankle inversion, and ankle eversion strength, with results displayed in **FIGURE 2**.[30] The mean differences for ankle dorsiflexion (–10.9 N), ankle inversion (–18.0 N), and ankle eversion (–30.3 N) indicated that those with plantar heel pain had less ankle strength than those without plantar heel pain. However, the

TABLE 2 Quality Assessment Checklist

Study	Criteria*: 1	2	3	5†	6	7	10	11	12	15	16	18	20	21	22	25	Total, %‡
Irving et al[18]	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	94
Sullivan et al[30]	Y	Y	Y	Y	Y	Y	Y	U	U	N	Y	Y	Y	Y	Y	Y	82
Kibler et al[21]	Y	Y	Y	N	N	N	U	U	U	N	Y	N	U	U	U	U	35
Allen and Gross[1]	Y	Y	Y	Y	Y	Y	Y	U	U	N	Y	Y	Y	Y	Y	Y	76
McClinton et al[23]	Y	Y	Y	Y	Y	Y	Y	U	U	N	Y	Y	Y	Y	Y	Y	76
Chang et al[4]	Y	Y	Y	Y	Y	Y	Y	U	N	Y	Y	Y	Y	U	U	U	82
Cheung et al[5]	Y	Y	N	Y	Y	Y	Y	U	N	U	Y	Y	Y	U	U	Y	65

Abbreviations: N, no (criterion not satisfied, score of 0); U, unavailable (criterion unavailable, score of 0); Y, yes (criterion satisfied, score of 1).
Criteria for the Downs-Black quality assessment are included in* **APPENDIX A.
†If the criterion is met, a score of 2 is given.
‡Percentage score out of 17, as item 5 counts for a score of 2.

TABLE 3 GRADE Evidence Profile: Strength and Size Comparisons in Those With Heel Pain and Those Without (Controls)

Outcome/Trials, n	Quality Assessment: Limitations	Inconsistency	Indirectness	Imprecision	Publication Bias	Summary of Findings, n: PHP	Control	SMD*	GRADE
Muscle strength									
Hallux plantar flexion (n = 2)	Very serious†	Not serious	Serious‡	Serious§	Undetected	228	97	Not pooled	Very low
Lesser toe plantar flexion (n = 3)	Very serious†	Not serious	Serious‡	Serious§	Undetected	248	117	Not pooled	Very low
Ankle dorsiflexion (n = 1)	Very serious†	NA	NA	NA	Undetected	199	70	Not pooled	Very low
Ankle inversion (n = 1)	Very serious†	NA	NA	NA	Undetected	199	70	Not pooled	Very low
Ankle eversion (n = 1)	Very serious†	NA	NA	NA	Undetected	198	70	Not pooled	Very low
Ankle plantar flexion torque (n = 1)	Very serious†	NA	NA	NA	Undetected	43	45	Not pooled	Very low
Calf endurance: single-leg heel raise (n = 2)	Serious‖	Serious¶	Not serious	Serious§	Undetected	279	150	0.01 (–0.56, 0.59)	Very low
Muscle size									
Forefoot (n = 2)	Very serious†	Serious¶	Serious‡	Serious§	Undetected	18	18	Not pooled	Very low
Rearfoot (n = 2)	Very serious†	Serious¶	Serious‡	Not serious	Undetected	18	18	Not pooled	Very low
Total foot (n = 2)	Very serious†	Serious¶	Serious‡	Not serious	Undetected	18	18	Not pooled	Very low

Abbreviations: GRADE, Grading of Recommendations Assessment, Development and Evaluation; NA, not applicable; PHP, plantar heel pain; SMD, standardized mean difference.
**Values in parentheses are 95% confidence interval.*
†Methodological quality of studies was less than 85%.
‡Studies used different methods and/or measures to evaluate outcomes.
§The extremes of the confidence intervals represent different conclusions.
‖Methodological quality of studies was less than 100%.
¶Confidence intervals show minimal overlap.

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ankle dorsiflexion result was not statistically significant. The Cohen's *d* was small (0.22) for ankle dorsiflexion, medium (0.42) for ankle inversion, and medium (0.60) for ankle eversion.[30]

Ankle Plantar Flexion Torque

One study assessed ankle plantar flexion torque using an isokinetic dynamometer at 2 constant velocities: 60°/s and 180°/s.[21] The unit of measurement was foot-pounds, which represents the torque created by 1 lb of force acting at a perpendicular distance of 1 foot from the point of rotation (approximately 1.36 Nm). The mean differences between groups of −21.9 ft-lb at 60°/s and −7.9 ft-lb at 180°/s indicated that those with plantar heel pain produced less force than those without plantar heel pain.[21] Insufficient data were reported to enable CIs and Cohen's *d* to be calculated.[21]

Calf Endurance

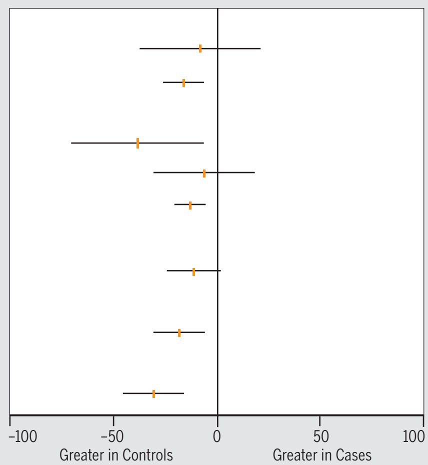
Three studies assessed calf endurance.[18,23,30] Two different tests were applied to assess calf endurance: a single-leg heel raise test and a rocker-board plantar flexion test.

Calf musculature endurance measured by the single-leg heel raise test was assessed in 2 studies (**FIGURE 3**).[18,30] Meta-analysis found a nonsignificant difference in calf endurance between people with and without plantar heel pain (standardized mean difference, 0.01; 95% CI: −0.56, 0.59). There was considerable heterogeneity between the 2 studies, with an I^2 value of 87%.[15]

Meta-analysis was not performed for the rocker-board plantar flexion test because there was only 1 study available.[23] McClinton et al[23] found a significant decrease in the number of repetitions that participants with plantar heel pain could perform, indicating that participants with heel pain had reduced calf endurance when compared to participants

Toe and Ankle Strength

	Cases		Controls		
Subgroup/Study	Mean ± SD N	Total, n	Mean ± SD N	Total, n	MD IV, Random (95% Confidence Interval)
Hallux plantar flexion					
McClinton et al[23]	19.6 ± 53.9	27	27.5 ± 53.9	27	−7.90 (−36.65, 20.85)
Sullivan et al[30]	152.3 ± 35.2	201	168.1 ± 35.3	70	−15.80 (−25.39, −6.21)
Lesser toe plantar flexion					
Allen and Gross[1]	88 ± 40	20	126 ± 60	20	−38.00 (−69.60, −6.40)
McClinton et al[23]	13.7 ± 45.1	27	19.6 ± 45.1	27	−5.90 (−29.96, 18.16)
Sullivan et al[30]	114.5 ± 27.4	201	127.3 ± 26	70	−12.80 (−19.97, −5.63)
Ankle dorsiflexion					
Sullivan et al[30]	203 ± 52.4	199	213.9 ± 44.8	70	−10.90 (−23.67, 1.87)
Ankle inversion					
Sullivan et al[30]	156.6 ± 41.5	199	174.6 ± 45.9	70	−18.00 (−30.20, −5.80)
Ankle eversion					
Sullivan et al[30]	163.5 ± 45.7	198	193.8 ± 55.2	70	−30.30 (−44.71, −15.89)

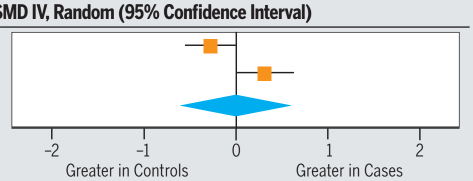


Abbreviations: IV, inverse variance; MD, mean difference.

FIGURE 2. Forest plot of toe and ankle absolute strength (Newtons).

Single-Leg Heel Raise

	Cases		Controls			
Study	Mean ± SD n	Total, n	Mean ± SD n	Total, n	Weight	SMD IV, Random (95% Confidence Interval)
Sullivan et al[30]	22.1 ± 9.3	199	24.6 ± 8.4	70	50.8%	−0.27 (−0.55, 0.00)
Irving et al[18]	17.3 ± 9.7	80	14.4 ± 8.7	80	49.2%	0.31 (0.00, 0.63)
Total*		279		150	100.0%	0.01 (−0.56, 0.59)



Abbreviations: IV, inverse variance; SMD, standardized mean difference.
**Heterogeneity: $\tau^2 = 0.15$, $\chi^2 = 7.72$, $df = 1$ ($P = .005$), $I^2 = 87\%$. Test for overall effect: $z = 0.05$ ($P = .96$).*

FIGURE 3. Forest plot (including meta-analysis) of the single-leg heel raise test (maximum repetitions).

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without (**APPENDIX D FIGURE 1**, available at www.jospt.org). When compared to the control group, the plantar heel pain group had a mean reduction in repetitions of −10.8 (95% CI: −19.0, −2.6), which equates to a medium Cohen's *d* of 0.70.

Muscle Size

Two studies assessed muscle size by using MRI.[4,5] No meta-analysis was performed due to heterogeneity between statistical methods. The first study, by Chang et al,[4] explored muscle volume (cubic centimeters) at 3 sites: the forefoot, rearfoot, and total foot (**FIGURE 4**). In addition, the study also measured cross-sectional area (square centimeters) of the tibialis posterior muscle (**APPENDIX D FIGURE 2**, available at www.jospt.org). The following mean differences were found: −4.1 cm^3 for the forefoot, −1.2 cm^3 for the rearfoot, −5.3 cm^3 for the total foot, and 0.0 cm^2 for the tibialis posterior muscle. None of these differences were statistically significant, although the sample size was small (8 participants in each group). The Cohen's *d* was small (0.23) for the forefoot, negligible (0.07) for the rearfoot, small (0.31) for the total foot, and negligible (0.00) for the tibialis posterior muscle.

The second study, by Cheung et al,[5] explored muscle volume normalized to body weight at 3 sites: the forefoot, rearfoot, and total foot (**FIGURE 5**). The mean difference at the forefoot was −49.6 mm^3/kg, at the rearfoot was −195.7 mm^3/kg, and for the total foot was −245.3 mm^3/kg. The differences in volume for the rearfoot and total foot muscles were statistically significant. The Cohen's *d* was small (0.30) for the forefoot, very large (1.11) for the rearfoot, and large (0.90) for the total foot.

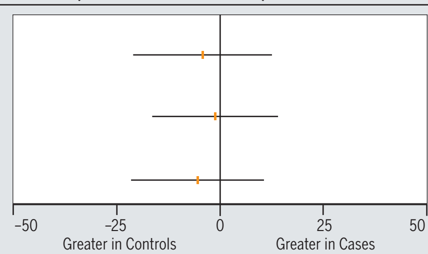
DISCUSSION

This systematic review investigated the muscle strength differences between people with and without plantar heel pain. People with plantar heel pain had weaker foot musculature than those without plantar heel pain. However, there was substantial heterogeneity between the studies and inconsistency in the findings, which indicates that further research is needed to improve the estimates and precision of the overall findings.

Specifically, the analysis of lesser toe and hallux plantar flexion strength consistently showed that participants with plantar heel pain had less strength.[1,23,30] Moreover, the 3 individual studies that assessed lesser toe plantar flexion strength had high quality, which strengthens the evidence that those with plantar heel

Muscle Volume

	Cases		Controls		
Subgroup/Study	Mean ± SD cm^3	Total, n	Mean ± SD cm^3	Total, n	MD IV, Random (95% Confidence Interval)
Forefoot					
Chang et al[4]	63.4 ± 14.8	8	67.5 ± 18.9	8	−4.10 (−20.73, 12.53)
Rearfoot					
Chang et al[4]	44.6 ± 13.3	8	45.8 ± 17.4	8	−1.20 (−16.38, 13.98)
Total foot					
Chang et al[4]	108 ± 14.1	8	113.3 ± 18.2	8	−5.30 (−21.25, 10.65)

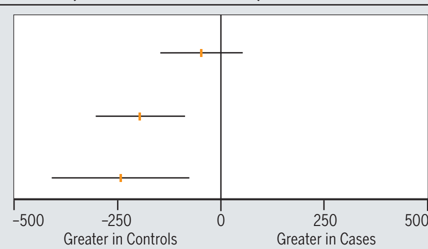


Abbreviations: IV, inverse variance; MD, mean difference.

FIGURE 4. Forest plot of muscle volume of foot regions (cubic centimeters).

Muscle Volume Normalized to Body Weight

	Cases		Controls		
Subgroup/Study	Mean ± SD mm^3/kg	Total, n	Mean ± SD mm^3/kg	Total, n	MD IV, Random (95% Confidence Interval)
Forefoot					
Cheung et al[5]	1091.2 ± 169.51	10	1140.8 ± 149.48	10	−49.60 (−199.8, 100.6)
Rearfoot					
Cheung et al[5]	746.8 ± 129.18	10	942.5 ± 208.02	10	−195.70 (−358.4, −33.0)
Total foot					
Cheung et al[5]	1838 ± 277.08	10	2083.3 ± 258.7	10	−245.30 (−497.1, 6.5)



Abbreviations: IV, inverse variance; MD, mean difference.

FIGURE 5. Forest plot of muscle volume of foot regions normalized to body weight (cubic millimeters per kilogram).

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pain have weaker lesser toe plantar flexion. However, due to the small number and cross-sectional nature of the studies, it cannot be inferred that weakness of the lesser toe plantar flexors causes plantar heel pain. Furthermore, the GRADE rating for this outcome was very low, which suggests that the strength of this evidence is weak and that future research is likely to change this finding.

Regarding calf endurance, the meta-analysis found no difference between those with and without plantar heel pain.[18,30] In this review, 1 study (n = 160 participants)[18] found a small standardized mean difference (0.31); that is, those with plantar heel pain performed more single-leg heel raise repetitions than those without. A larger study (n = 269 participants)[30] also found a small standardized mean difference (–0.27), but in favor of the control group; that is, participants without plantar heel pain performed more single-leg heel raise repetitions. While the findings of these studies are inconsistent, their methods were the same, and both had high-quality assessment scores. Nevertheless, the conclusion from pooling their findings in a meta-analysis is that calf endurance does not appear to differ between those with plantar heel pain and those without.

Muscle strength can also be inferred by measuring muscle size, namely, muscle volume or cross-sectional area.[10] Only 2 included studies measured muscle size on MRI.[4,5] Both studies found a reduction in muscle volume of foot muscles in those with plantar heel pain.[4,5] While more research needs to be conducted to provide more precise estimates, these initial studies indicate that there may be deficits in the volume of foot muscles in those with plantar heel pain.

Considering all the above findings, weaker foot muscles may be important in the development and continuation of plantar heel pain. The digital plantar flexor muscles acting on the foot generate force in the toes and provide stability and support to the medial longitudinal arch.[14,19,20] Therefore, if the muscles acting on the foot are weakened, noncontractile tissues such as the plantar fascia and the plantar fat pad of the heel are subject to increased load, which may contribute to plantar heel pain.[2,22]

This review has 3 key strengths. First, it investigated all measurable variables of muscle strength (force production, torque, muscle endurance, and muscle size) in those with and without plantar heel pain. Second, the methodological quality of the included studies (only 1 of 7 scored below 65% on the quality assessment) indicates that the findings are of moderate quality.[7] Two items consistently did not achieve a good rating on quality assessment. First, only 1 study[30] recruited participants who were representative of the entire population, which limits the generalizability of the results. Second, only 1 study[4] blinded the assessors, which could have led to assessor bias. Future studies should recruit from the general population and blind assessors to group allocation. Finally, this review utilized the GRADE approach to rate the strength of the evidence.[13]

This review has 4 limitations that need to be considered. First, there was considerable heterogeneity between studies. Of the 5 included studies that measured muscle strength, only 2 followed similar protocols for the measurement of variables of interest, which precluded meta-analysis. This issue highlights the need for valid and reliable measures of strength assessment and consistent methods in future research.[29] Second, substantial inconsistency in the findings of the included studies indicates a need for further research to improve confidence in the overall findings. Future studies with larger sample sizes and increased homogeneity in methods would address this. Third, the Downs-Black quality assessment index that we used to assess methodological quality of the included studies, like all such tools to assess methodological quality of cross-sectional observational studies, has not been validated. However, in the absence of a valid tool to assess the types of studies included in our systematic review,[34] we elected to use the Downs-Black index to report study quality. Further, we removed items from the Downs-Black index that did not relate to the design of the studies included in our review and are not certain about the effect of this on the validity of the tool. Nevertheless, in addition to the overall quality scores that the Downs-Black assessments provided for each study, we provided ratings for the individual items of the tool, so that readers could make a more qualitative assessment of each study's quality (**TABLE 2**). Finally, due to the cross-sectional nature of the studies, it cannot be inferred that foot muscle weakness causes plantar heel pain. Accordingly, we currently do not know whether strengthening foot or leg muscles may benefit people with plantar heel pain.

Taken as a whole, after the application of the GRADE tool, the overall evidence from these studies indicates that further research is likely to have an important impact on our confidence in the findings (ie, further research could impact the point estimates observed and the precision of these estimates).[13] Accordingly, future research investigating the role of muscle strength in plantar heel pain is warranted. If muscle strength was found to be deficient in people with plantar heel pain, it would help to determine whether strengthening foot or leg muscles could be of benefit in this population.

CONCLUSION

This review found very low–quality evidence that individuals with plantar heel pain have weaker foot musculature than those without plantar heel pain. Overall, inconsistency in the findings from the included studies suggests that further high-quality research may change the findings of this review. Future studies should compare muscle strength between those with and without plantar heel pain using valid and

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reliable methods and with appropriate sample sizes. ◉

KEY POINTS

FINDINGS: There is very low–quality evidence that individuals with plantar heel pain have weaker foot musculature than those without.

IMPLICATIONS: Further research assessing muscle strength in those with and without plantar heel pain may lead to better understanding of the pathology of this condition and the development of improved treatments.

CAUTION: Due to heterogeneity and imprecision in the findings of the included studies, more research needs to be undertaken. In addition, because the included studies are cross-sectional, no inference can be made regarding causality.

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APPENDIX A

DOWNS-BLACK[7] INDEX

Question	Excluded From Review?
1. Is the hypothesis/aim/objective of the study clearly described?	
2. Are the main outcomes to be measured clearly described in the Introduction or Methods section?	
3. Are the characteristics of the patients included in the study clearly described?	
4. Are the interventions of interest clearly described?	Yes
5. Are the distributions of principal confounders in each group of subjects to be compared clearly described?	
6. Are the main findings of the study clearly described?	
7. Does the study provide estimates of the random variability in the data for the main outcomes?	
8. Have all important adverse events that may be a consequence of the intervention been reported?	Yes
9. Have the characteristics of patients lost to follow-up been described?	Yes
10. Have actual probability values been reported (eg, .035 rather than <.05) for the main outcomes, except where the probability value is less than .001?	
11. Were the subjects asked to participate in the study representative of the entire population from which they were recruited?	
12. Were those subjects who were prepared to participate representative of the entire population from which they were recruited?	
13. Were the staff, places, and facilities where the patients were treated representative of the treatment the majority of patients receive?	Yes
14. Was an attempt made to blind study subjects to the intervention they have received?	Yes
15. Was an attempt made to blind those measuring the main outcomes of the intervention?	
16. If any of the results of the study were based on "data dredging," was this made clear?	
17. In trials and cohort studies, do the analyses adjust for different lengths of follow-up of patients, or in case-control studies, is the time period between the intervention and outcome the same for cases and controls?	Yes
18. Were the statistical tests used to assess the main outcomes appropriate?	
19. Was compliance with the intervention(s) reliable?	Yes
20. Were the main outcome measures used accurate (valid and reliable)?	
21. Were the patients in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited from the same population?	
22. Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same period of time?	
23. Were study subjects randomized to intervention groups?	Yes
24. Was the randomized intervention assignment concealed from both patients and health care staff until recruitment was complete and irrevocable?	Yes
25. Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?	
26. Were losses of patients to follow-up taken into account?	Yes
27. Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%?	Yes

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APPENDIX B

GRADE CRITERIA

Each outcome was investigated for limitations (risk of bias), inconsistency, indirectness, imprecision, publication bias, and magnitude of effect. Outcomes were downgraded 1 level for limitations if the included studies scored less than 100% in methodological quality according to the Downs-Black checklist. Outcomes were downgraded 2 levels if the included studies scored less than 85% in methodological quality. Outcomes were downgraded 1 level for inconsistency if there was significant heterogeneity (ie, I^2 greater than 40%).[12] Outcomes were downgraded for indirectness if there were significant differences between the populations, interventions, or outcomes measured across studies.[11] Outcomes were downgraded for imprecision if the confidence intervals represented different conclusions. Outcomes were downgraded for publication bias if there was obvious industry involvement. Outcomes for each comparison were classified into 4 categories: (1) high (we are very confident that the true effect lies close to the estimate of effect), (2) moderate (we are moderately confident in the effect estimate; further research is likely to change the estimated effects), (3) low (our confidence in the effect estimate is limited; further research is very likely to change the estimated effects), and (4) very low (we have very little confidence in the effect estimate; further research is very likely to change the estimated effects, and current effects provided are uncertain).[13]

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APPENDIX C

CHARACTERISTICS OF THE INCLUDED STUDIES

Study	Sample Size	Participant Characteristics*	Measurement Details	Measurement Units
Kibler et al[21]	PHP group: n = 43 (11 female, 32 male) Control group: n = 43 (11 female, 32 male)	PHP group: age, 31 y (range, 21-44 y); athletic pursuit: 35 running, 5 racquet sports, 3 basketball Control group: "matched by age and sex" to PHP group; athletic pursuit: 5 running, 26 racquet sports, 9 basketball, 5 aerobics	A Cybex dynamometer was used, with peak torque measurements taken at 2 constant velocities: 60°/s and 180°/s	Foot-pounds
Allen and Gross[1]	PHP group: n = 20 (16 female, 4 male) Control group: n = 20 (16 female, 4 male)	PHP group: age, 44.9 ± 9.2 y; BMI, 28.5 ± 7.0 kg/m^2; duration of symptoms, 19.9 ± 33.2 mo (range, 2-150 mo) Control group: age, 43.1 ± 8.0 y; BMI, 25.9 ± 3.8 kg/m^2 Authors did not present height and weight data for each group (only presented for men and women separately in each group)	An electronic strain gauge to measure muscle strength (ie, force) was fitted to a specifically designed apparatus. Participants were seated with the leg and foot stabilized. Participants were asked to pull down with their toes on an aluminum bar attached to the strain gauge, and the force generated was recorded. Participants performed 5 trials of the test, and the mean was calculated	Newtons
Irving et al[18]	PHP group: n = 80 (47 female, 33 male) Control group: n = 80 (47 female, 33 male)	PHP group: age, 52.3 ± 11.7 y; height, 1.69 ± 0.09 m; weight, 84.8 ± 17.4 kg; BMI, 29.8 ± 5.4 kg/m^2; Foot Posture Index, 2.4 ± 3.3† Control group: age matched (±2 y); height, 1.69 ± 0.08 m; weight, 79.0 ± 16.0 kg; BMI, 27.5 ± 4.9 kg/m^2; Foot Posture Index, 1.1 ± 2.3†	Muscle strength was determined by the proxy measure of calf muscle endurance, which was measured by the number of repetitions to fatigue using the standing heel-raise test. Participants were instructed to complete single-leg calf raises from the floor to maximum end range of motion until they were unable to perform any more	Number of repetitions
Chang et al[4]	n = 8 (7 female, 1 male) All participants had unilateral PHP; the contralateral (ie, healthy) limb was used as the control	Age, 44.9 ± 8.4 y; height, 165.1 ± 8.0 cm; weight, 75.6 ± 12.7 kg; duration of symptoms, 3.0 ± 3.7 y (range, 0.4-10.0 y)	T1-weighted magnetic resonance images taken of the feet, with 4-mm slice thickness. For intrinsic foot muscles, muscle volumes (a possible proxy for muscle strength) were estimated for the rearfoot, forefoot, and the entire foot. For the tibialis posterior, muscle cross-sectional areas were measured after eliminating tendon, bone, and fat from changes in signal intensity to identify structures other than muscle	Cubic centimeters for volume and square centimeters for cross-sectional area
Sullivan et al[30]	PHP group: n = 202 (134 female, 68 male) Control group: n = 70 (42 female, 28 male)	PHP group: age, 55 ± 13.5 y; height, 1.67 ± 0.09 m; weight, 79.7 ± 16.3 kg; BMI, 28.8 ± 5.1 kg/m^2; Foot Posture Index, 4.7 ± 3.3† Control group: age, 48 ± 17.1 y; height, 1.67 ± 0.1 m; weight, 71.8 ± 14.1 kg; BMI, 25.6 ± 3.8 kg/m^2; Foot Posture Index, 4.1 ± 3.4†	Two measures of muscle strength were used: (1) a handheld dynamometer to determine ankle dorsiflexion, inversion, eversion, and hallux and lesser digit plantar flexion strength; and (2) calf endurance (a proxy for strength) measured by the number of repetitions when performing the standard heel-raise test	Newtons for strength and number of repetitions for the standard heel-raise test
Cheung et al[5]	PHP group: n = 10 (5 female, 5 male) Control group: n = 10 (5 female, 5 male) All participants were experienced runners. Plantar heel pain group had bilateral chronic (≥2 y) pain. Control group had never incurred any running-related overuse injury	PHP group: age, 32.6 ± 5.4 y; height, 1.67 ± 0.09 m; weight, 63.8 ± 14.8 kg; weekly running distance, 29.7 ± 8.6 mi Control group: age, 34.5 ± 5.0 y; height, 1.71 ± 0.06 m; weight, 64.9 ± 7.0 kg; weekly running distance, 30.0 ± 18.3 mi	T1-weighted magnetic resonance images of the feet, taken with 4-mm slice thickness. All noncontractile tissue was excluded. Muscle volumes (a possible proxy for muscle strength) were calculated using the product of slice thickness and muscle cross-sectional area for each image. In order to minimize the effect of different body builds between participants, the primary measurement (ie, muscle volume) was divided by the weight of the participant	Cubic millimeters per kilogram

Table continues on page B4.

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APPENDIX C

Study	Sample Size	Participant Characteristics*	Measurement Details	Measurement Units
McClinton et al[23]	PHP group: n = 27 (18 female, 9 male) Control group: n = 27 (16 female, 11 male)	PHP group: age, 52 ± 14 y; BMI, 30.9 ± 4.8 kg/m^2; orthosis use, n = 24 (89%); duration of symptoms, >7 mo (56%) and >2 y (19%) Control group: matched by age, sex, and BMI; age, 50 ± 16 y; BMI, 28.9 ± 6.3 kg/m^2; orthosis use, n = 2 (7%)	Two measures of strength were used: (1) a modified paper grip test to assess hallux and lesser toe flexion strength (kilograms), and (2) a rocker-board plantar flexion test to assess ankle plantar flexion endurance (as a proxy for strength)	Kilograms for the modified paper grip test and number of repetitions for the rocker-board plantar flexion test

Abbreviations: BMI, body mass index; PHP, plantar heel pain.
**Values are mean ± SD unless otherwise indicated.*
†The Foot Posture Index was reported on a scale from −12 (highly supinated) to +12 (highly pronated), with the normal range being 0 to +5.

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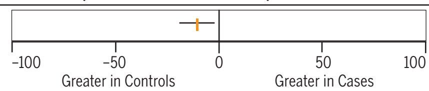
APPENDIX D

Rocker-Board Plantar Flexion Test

Study	Cases: Mean ± SD n	Cases: Total, n	Controls: Mean ± SD n	Controls: Total, n	MD IV, Random (95% Confidence Interval)
McClinton et al[23]	13 ± 15.4	27	23.8 ± 15.4	27	−10.80 (−19.01, −2.59)

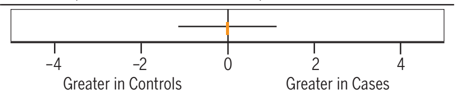


Abbreviations: IV, inverse variance; MD, mean difference.

FIGURE 1. Forest plot for the rocker-board plantar flexion test (maximum number of repetitions).

Muscle Cross-sectional Area

Study	Cases: Mean ± SD cm^2	Cases: Total, n	Controls: Mean ± SD cm^2	Controls: Total, n	MD IV, Random (95% Confidence Interval)
Chang et al[4]	4.3 ± 1.1	8	4.3 ± 1.2	8	0.00 (−1.13, 1.13)



Abbreviations: IV, inverse variance; MD, mean difference.

FIGURE 2. Forest plot for the muscle cross-sectional area of the tibialis posterior (square centimeters).

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Social Determinants of Health: If You Aren't Measuring Them, You Aren't Seeing the Big Picture

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Clinicians often assume that interventions directly influence the recovery of patients with musculoskeletal impairments. In reality, other factors may influence recovery more than the direct treatment provided.[1,6,8] The most powerful factor may be upstream effects such as economic stability, education, health and health care, neighborhood and built environment, and social and community context—commonly termed the social determinant of health (SDH). Although a single empirical pathway linking the collective impacts of the SDH to musculoskeletal health outcomes has not been established, our view is that they exert tremendous effects on physical therapy outcomes in practice and research. In this Viewpoint, we discuss the SDH and argue that recognizing the impact of SDHs on health behavior is vital to seeing the whole picture related to musculoskeletal recovery.

The SDH: A Primer

It is tempting to believe that medical care is the largest factor affecting musculoskeletal recovery. However, models that include SDH variables place the role of medical care in health and recovery only at 20%.[7,9] Estimates of the effects of other domains on health and recovery paint a picture much different from what we believe happens in the clinic: social and economic circumstances account for 40%, environmental factors account for 10%, and behavioral patterns account for 30%. Social determinants of health directly contribute to well-being and health outcomes, but they also influence health behaviors and lifestyle choices of individuals by making it easier or harder, and more or less desirable, to choose healthier behaviors over less healthy behaviors.[3] The SDH and the health behaviors that follow are the modifiable contributors to inequities in health and musculoskeletal recovery (**FIGURE**).

Addressing SDHs at the Patient Level

Social determinants of health affect every patient: they influence prognosis and suggest additional avenues for intervention. A variety of assessment tools have been developed, but none has been vetted through all steps of development and validation. The Institute of Medicine 25-item checklist consists of 6 domains, the Protocol for Responding to and Assessing Patients' Assets, Risks, and Experiences includes 21 items, and the Health Leads Screening Toolkit involves an item bank that can be used to focus on areas of interest. These tools provide a starting point, with recommended core domains such as food insecurity, housing instability, utility needs, and financial resource strain. The Social Interventions Research and Evaluation Network has created a useful overview and comparison of freely available tools.[10]

Societal trends, such as more volatile employment rates and unpredictable gaps in job stability, make it hard to predict which patients are at increased risk of exposure to adverse SDH factors. We

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encourage clinicians to engage their entire practice population rather than target subgroups.[2] Assessing SDHs is different from other forms of screening, because it can reveal adverse exposures and conditions that often require resources beyond the scope of traditional clinical care. Screening for the SDH without appropriate referral is ineffective and potentially unethical.[5] It is essential to integrate SDH screening with referral to community-based resources. In this way, the clinician can provide advice, refer the individual to other services, and facilitate access to services in a sensitive, culturally acceptable, and caring way.

Addressing SDHs at the Community Level

Clinicians, faculty, residents, and students need not limit their activities to within the 4 walls of the clinic. They should also serve as advocates and resources in the community. Start by asking, "What do my patients' communities need to be healthier?" Data to answer this question can be found in local public health offices, population-level surveys, and hospital planning departments. Answers to this question can also be found by engaging directly with members of the community to identify SDH concerns that are most impactful and important to them. Explore partnerships with community groups, health departments, and local leaders to create multistakeholder, community-wide initiatives that can have significant impacts. Involvement in community health needs assessment and health planning is one way to develop a common language and shared understanding of the dimensions driving the health needs of a community. There is no cookbook for this work; the needs of each community differ and require specific approaches.

Addressing SDHs in Research

Researchers are tasked with developing internally valid methods and externally generalizable results, which are often at odds in clinical research. Specifically related to the impact of the SDH, generalizing results from comparative effectiveness and physical therapy outcomes research is difficult in small, homogeneous convenience samples. Although randomization in clinical trials makes it more likely that confounders in both groups are balanced, the effectiveness of treatments for musculoskeletal disorders can be moderated by SDH factors.

The characteristics of the sample can interact with the experimental or control intervention applied, which can moderate the overall treatment effect.[4] In observational studies, SDH factors may be unaccounted for in the design and analysis, thus impact the results in unknown and unmeasured ways. For this reason, the potential impact of SDHs on outcomes in experimental studies and on risk in observational studies is unknown unless measured.

Study designs should reflect the needs of individuals who are enrolled in the trials.

Economic stability. Economic resources allow for room to engage in healthy behaviors that promote recovery. Lower SE position may increase the chances of absence from work due to musculoskeletal injury. In addition, lower SE position may create barriers to seeking physical therapy care, including difficulty scheduling, time in treatment to achieve recovery, and lack of insurance coverage for visits, ultimately contributing to cycles of SE disadvantage.

Education. Individuals who are more educated tend to have increased financial, emotional, psychological, and social resources. These resources allow them to make better behavior-based lifestyle choices, which contribute to positive physical and psychological well-being. Conversely, poorer recovery from musculoskeletal conditions can interfere with the educational process, potentially creating cycles of disadvantage. In addition, lower levels of health literacy are associated with greater levels of opioid misuse and experience of pain in those with chronic pain.

Health care. A systematic bias against the treatment of people of color, which results in substandard care, exists. Health care infrastructure is often diverted to higher-income neighborhoods, which results in fewer clinicians in low-income neighborhoods. Moreover, these clinicians are more likely to be less educated and less qualified than those in higher-income neighborhoods. Access to care may also be a barrier, because seeing someone—anyone—can be expensive. More than half of all unpaid personal debts sent to collection agencies are for medical bills. Even for those with health insurance, over one third of Americans with difficulty paying medical bills had to choose between paying those bills and paying for food, heat, or housing. These barriers may limit access to needed health care services, which may increase the risk of poor health outcomes and increased health disparities.

Neighborhood and built environment. People in lower SE communities have limited access to quality housing stock and tend to live in neighborhoods designed without safe outdoor environments to promote and enable physical activity that contributes to greater levels of overall health. Poor urban planning and inadequate housing are consistently associated with increased social isolation and the physical and mental health problems that follow. Additionally, the availability of healthy food and an awareness of food choices related to general health and disease management assist in reducing the prevalence of noncommunicable diseases.

Social and community context. Especially in childhood, exposure to stressful social conditions (adverse childhood experiences) can affect brain development and may lead to many chronic diseases. It may even increase the number of painful medical conditions developed later in life. What may be the most pernicious consequence of these stressful experiences is that they increase risks for these same stressors in the next generation, leading to a cycle of intergenerational vulnerability. Further, connectedness to others, prevailing social norms, and a sense of belonging and identification within the community also exert strong influence over health and health behaviors. Accepting positive health messages and making healthy decisions are strongly associated with the acceptance of these behaviors by the people individuals consider their community. Thus, population-based strategies can be effective at exerting influence over individuals' choices related to health behaviors, including physical activity, diet, and smoking.

FIGURE. Key domains associated with the social determinants of health. Abbreviation: SE, socioeconomic.

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For example, SDH factors such as access to care and transportation may influence follow-up and completeness of data collection from study participants. Engage different stakeholders, using strategies to increase participation of underserved and often disadvantaged communities and populations to ensure representative samples. Constructs of SDH, health behavior, and adherence to the intervention of interest should be measured and quantified across participants to account for their influence on research results.

Addressing SDHs in Policy

Policy makers paint with a large brush and, in doing so, exert influence at the macroscopic level. While this is an efficient way to quickly change downstream behavior, there can be unintended consequences for those who are most vulnerable. Social conditions affect communities' health and need to be considered when developing policy related to outcomes and expectations for concepts of health, health promotion, and prevention. Health in All Policies is one strategy that has been proposed to evaluate all public policies through a population health lens. However, the approach is challenging, and definitions of success are not universal. Because of the abstract nature and changing metric of concepts related to prevention and health promotion, policy makers need to engage constituency groups to ensure that legislation will result in what is intended.

The Compounding Effects of the SDH

The time has come to recognize that many factors other than direct interventions from clinicians play a role in musculoskeletal recovery. The SDHs quickly compound around an individual or community. Positive findings in one area create a likelihood of success in others. Negative findings in one area contribute to a likelihood of failure in others. The influence that SDHs exert on communities and patients filters down through health behaviors and individual choices that affect musculoskeletal recovery. Let us work together to expand our view of patients to include the big picture, recognizing that social and environmental contexts play a larger role in musculoskeletal recovery than we expect.

Key Points

- Musculoskeletal recovery is complicated and is rarely associated with only 1 factor.
- Social determinants of health may be major factors in musculoskeletal recovery.
- Social determinants of health involve 5 key domains: economic stability, education, health care access, neighborhood and environment, and social and community context.
- Integrating screening for SDHs and referral to community-based resources is one avenue for clinicians to address SDHs. ◉

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Reduced Trunk Coupling in Persons With Recurrent Low Back Pain Is Associated With Greater Deep-to-Superficial Trunk Muscle Activation Ratios During the Balance-Dexterity Task

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The impact of recurrent low back pain (LBP) on society has long been recognized. In a recent global health study, out of 291 conditions studied, LBP ranked as the greatest contributor to global disability.[29] The annual prevalence of activity-limiting LBP has been reported at 38%.[28] In a study of US health care spending in 2013, LBP and neck pain accounted for $87.6 billion—the highest spending level for any musculoskeletal condition and the third highest of any health condition behind diabetes and ischemic heart disease.[12] A major contributor to the continued societal impact of LBP is persistent or recurrent episodic pain in the low back after the first episode. A recent systematic review examined studies of recovery from a first acute episode of LBP and reported recurrence rates between 22.1% after 3 months and 77.1% at 3-year follow-up.[10] Researching persons with recurrent LBP during symptom remission may allow the removal of current pain and the identification of residual aspects of motor control dysfunction and psychosocial factors.

BACKGROUND: Motor control dysfunction persisting during symptom remission in persons with recurrent low back pain (LBP) may contribute to the recurrence of pain.

OBJECTIVES: To investigate trunk control in persons in remission from recurrent LBP and in back-healthy controls using a dynamic, internally driven balance task. No differences in task performance were expected between groups, but it was hypothesized that persons with recurrent LBP would exhibit greater trunk coupling, consistent with a trunk-stiffening strategy.

METHODS: In this cross-sectional controlled laboratory study, persons with and without recurrent LBP (n = 19 per group) completed the balance-dexterity task, which involved balancing on one limb in standing while compressing an unstable spring with the other. Task performance measures included center-of-pressure velocity under the stance limb and vertical force variability under the spring. Trunk coupling was quantified with the coefficient of determination (R^2) of an angle-angle plot of thorax-pelvis frontal plane motion. Fine-wire and surface electromyography captured activations of paraspinals and abdominals.

RESULTS: There were no differences between groups for any task performance measure. The group in remission from recurrent LBP exhibited reduced trunk coupling, or more dissociated thorax and pelvis motion, compared to the healthy control group (P = .024). Trunk coupling in this group was associated moderately with the lumbar multifidus-to-erector spinae activation ratio (r = 0.618, P = .006) and weakly with the internal oblique-to-external oblique ratio (r = 0.476, P = .046).

CONCLUSION: The balance-dexterity task is a submaximal, internally driven unstable balance task during which more dissociated trunk motion was observed in persons in remission from recurrent LBP. Findings underscore the task-dependent nature of trunk control research and assessment in persons with recurrent LBP. *J Orthop Sports Phys Ther 2019;49(12):887-898. Epub 15 May 2019. doi:10.2519/jospt.2019.8756*

KEY WORDS: *balance, perturbation, trunk control*

When pain is in remission in this population, persistent motor control dysfunction may contribute to the recurrence of pain. Using mechanical perturbations through support-surface translation or trunk-release paradigms, multiple groups have reported increased trunk muscle co-contraction[30,44] and stiffening behavior[21,53] in persons with recurrent LBP whose symptoms are in remission. Prospectively, prolonged activation of abdominal muscles after a trunk release was associated

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with LBP recurrence within 2 to 3 years, with the risk of LBP increasing 3% for every millisecond that abdominal shutoff was delayed.[6] Increasing trunk stiffness (greater control of, or resistance to, trunk displacement)[27] in the short term after an acute episode of LBP may protect damaged tissue, but residual increased stiffness after symptoms subside may increase spine loading and decrease loading variability, contributing to further degeneration and pain recurrence.[22,27]

Findings supporting the presence of a stiffening strategy in this population, meaning the adoption of greater trunk stiffness, are mixed, however, and seem to be dependent on task, symptom status, and plane of motion analyzed. In persons with symptomatic LBP performing unstable seated balance tasks, researchers observed increased trunk stiffness that was associated with increased trunk muscle cocontraction.[16-18] In a systematic review mixing research in persons with both current LBP and a history of LBP performing a variety of functional tasks, overall conclusions included reduced lumbar range of motion, suggesting increased trunk stiffness.[32] During gait, findings depend on the population studied. In persons with current pain, correlations of thorax and pelvis motion, a kinematic measure used to describe stiffness, increased.[13,52] Those in whom pain was in remission exhibited no differences in how the thorax and pelvis moved relative to each other.[7] In studies that observed a stiffening strategy, muscle activation patterns often included increased superficial trunk muscle activity. Unstable standing balance revealed decreased activity of the transverse abdominis and internal oblique (IO), but increased activity of the more superficial external oblique (EO), in the LBP group.[14] Modeling of a quick release of the trunk from a supported position revealed that the increased coactivation adopted by symptomatic persons stabilized the lumbar spine.[53] These findings suggest a pattern of overactive superficial trunk musculature, resulting in trunk stiffening in persons with recurrent LBP, but this may be more consistent while symptomatic or during large external perturbations. Also, the majority of these tasks induced primary motion or perturbation in the transverse plane, with a few studies investigating sagittal plane perturbation and frontal plane analyses limited primarily to studies of single-limb stance.

Other investigational tasks, however, have evoked reduced trunk stiffness associated with impaired deep trunk muscle recruitment. In anticipation of and response to sudden trunk loading, MacDonald et al[36] reported reduced or entirely absent lumbar multifidus (LM) activation in persons in remission from recurrent LBP. In an unstable sitting task, greater thoracolumbar movements and reduced trunk stiffness were associated with reduced deep-to-superficial paraspinal muscle activation ratios.[58] A study of walking turns in our lab revealed no difference in movement variability or in-phase trunk coupling between groups, suggesting no difference in trunk-stiffening strategy.[50] When walking speed was increased, control participants increased LM activation duration, but persons whose recurrent LBP was in remission reduced the duration of activation.[49] Conflicting conclusions about alterations in trunk control in this population contribute to confusion in research and clinical practice. Recent commentaries suggest that both "tight" (described here as stiffer) and "loose" (described here as less stiff or more variable) control strategies may be present in different patient subgroups or in different task contexts.[55]

These conflicts between studies that have observed tight and loose motor control strategies may be partially reconciled, therefore, by synthesizing research findings and by recognizing the importance of the tasks used in the studies. A seminal modeling study by Cholewicki and McGill[5] suggests that lower-effort tasks place the lumbar spine at injury risk due to intervertebral instability and that higher-effort tasks place the lumbar spine at risk due to tissue failure. This is consistent with the findings that increased demands on postural control, especially through externally perturbed posture, evoked increases in trunk stiffness and that lower-demand continuous balance tasks showed mixed findings, depending on current symptoms. Though it has long been recognized that participant heterogeneity has been problematic for LBP research, tasks to investigate mechanical, physiological, and psychosocial characteristics are needed, as well as novel tasks that evoke dysfunctional trunk control strategies in ecological contexts along a continuum of mechanical, physiological, and psychosocial demands. In this context, laboratory research tasks must have these characteristics carefully evaluated, and new tasks should be developed with task characteristics and plane of motion in mind.

The balance-dexterity task,[47] designed by combining single-limb balance with the lower extremity dexterity test,[35] serves as an ideal task to observe aspects of submaximal, unstable postural control. Adding the challenge of dexterous force control of the lower limb to single-limb balance provides increased postural demands and evokes greater trunk motion, making observing trunk control strategies in the frontal plane more feasible than traditional single-limb stance.[33,47] The purpose of this study was to investigate trunk control in persons with recurrent LBP in symptom remission and in back-healthy control participants using the balance-dexterity task. It was hypothesized that there would be no differences in task performance, but that persons with recurrent LBP would exhibit greater trunk coupling and associated greater superficial trunk muscle activity, in line with a trunk-stiffening strategy.

METHODS

This cross-sectional controlled laboratory study was reviewed and approved by the University of Southern California's Health Sciences Campus Institutional Review Board. After providing informed consent, participants with nonspecific recurrent LBP and matched back-healthy control participants with no history of LBP in the past year[41] were recruited from student extracurricular groups (eg, undergraduate Pre-Physical Therapy Club), flyers, and physical therapy clinics. Participants with recurrent LBP had to have recalled at least 2 episodes of pain, localized to the area between the lower ribcage and horizontal gluteal fold, per year for at least 1 year, but had to have experienced pain for less than half of the days in the previous 6 months (to distinguish chronicity from recurrence[11]). Participants reported episodes of pain severe enough to limit function, based on questions in the National Institutes of Health Task Force recommended minimum data set[11] and on the Oswestry Disability Index,[15] and were in symptom remission at the time of testing and for the preceding 7 days (pain of less than 1.5/10 on a visual analog scale [VAS][4]). Exclusion criteria included being older than 45 years of age; low back surgery; a radiological or clinical diagnosis of spinal stenosis, scoliosis, malignancy, infection, or radiculopathy; current or previous musculoskeletal injury or surgery affecting locomotion or balance; a history of diabetes mellitus, rheumatic joint disease, any blood-clotting disorder or current anticoagulant therapy, or polyneuropathy; or current pregnancy. A pre hoc power analysis determined a sample size of 19 per group, with power set at β = .8 after data from 4 pilot participants in each group were collected.

Participants were instrumented with a full-body retroreflective marker set, as well as surface electromyography (EMG) of the EO, rectus abdominis, gluteus maximus, and gluteus medius and fine-wire EMG of the IO, LM, and erector spinae (ES) at the level of L4 (3000-Hz wireless EMG; Noraxon USA Inc, Scottsdale, AZ). Surface EMG data were collected with bipolar Ag/AgCl electrodes, with an interelectrode distance of 22 mm and placed per guidelines from the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles project.[48] Fine-wire EMG data were collected with a pair of fine-wire electrodes (50-μm Ni/Cr alloy wires insulated with nylon) that were sterilized and inserted with a 25-gauge hypodermic needle, with the distal 2 mm exposed. Insertions were done under ultrasound guidance, and protocols were adapted from Perotto.[43] All muscles were instrumented on the side contralateral to the participant's preferred kicking limb, hereafter referred to as the stance side. Motion data were captured with an 11-camera Oqus system (250 Hz; Qualisys AB, Gothenburg, Sweden), and force data were captured with 2 force plates (3000 Hz; Advanced Mechanical Technology, Inc, Watertown, MA).

The balance-dexterity task device and procedures have been described previously.[47] Briefly, participants completed a 30-second trial of double-limb standing (preferred stance width) and three 30-second trials of single-limb standing on the stance side. Participants were introduced to the balance-dexterity task, which used a custom device with a spring mounted between 2 boards (Compression Spring model 805; Century Spring Corporation, Commerce, CA). Participants were shown real-time feedback of the vertical force under the spring and were instructed as follows: "While standing on one leg, compress this spring so that the line is first as high, then as stable as possible" (**FIGURE 1**). Each trial lasted 20 to 25 seconds. After 1 familiarization trial and 5 practice trials, the mean of the middle 50% of the last 3 practice trials was used to calculate an individual's reproducible, submaximal compression. After practice, participants used a VAS to report how difficult the task was (0, "not difficult at all" to 10, "extremely difficult"), how confident they were that they could complete the task successfully (0, "not confident at all" to 10, "extremely confident"), and how much attention the task required (0, "no attention at all" to 10, "all my attention"). Participants then completed 5 trials in which a dotted line indicating this reproducible, submaximal compression was shown as a goal, with these instructions: "While standing on one leg, compress this spring so that the line is as stable as possible directly over the dotted goal line." Three trials were interspersed in which the spring was replaced with a stable block of the same height, and the same instructions were given.

Trials were trimmed so that the middle 50% of the task was analyzed. Kinematic and force-plate data were low-pass filtered with cutoff frequencies of 12 Hz and 50 Hz, respectively. Surface and fine-wire EMG data were band-pass filtered between 20 and 500 Hz and 20 and 1000 Hz, respectively, using a dual-pass, fourth-order Butterworth filter. After filtering, EMG data were rectified and smoothed with a moving weighted average window of 500 milliseconds. Signals were normalized to averaged signal amplitude during the stable-block trials. This allowed EMG amplitude to be interpreted as a response to the added challenge of dexterous force control, not to the body position or vertical force production. This also avoided limitations of referencing EMG activity to maximal contractions, which are less reliable than submaximal reference contractions in a population with LBP.[8]

Average magnitude of the center-of-pressure (COP) resultant velocity from

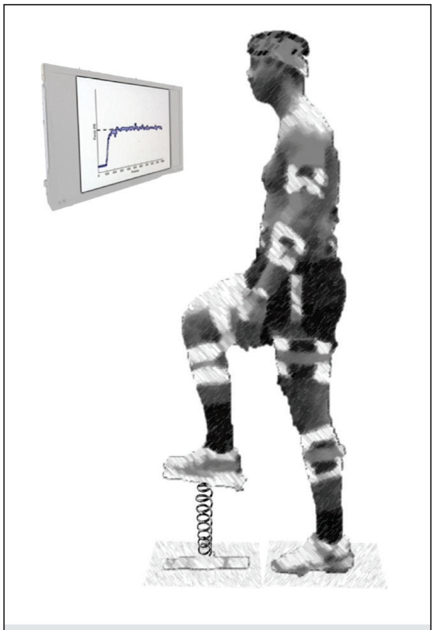

FIGURE 1. The balance-dexterity task. Adapted with permission from Rowley et al.[47]

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the stance limb was calculated. Dexterous force control was measured using the vertical force produced under the spring and quantified as root-mean-square error (RMSE) from the reproducible, submaximal compression goal line and coefficient of variation (CV). Trunk control was quantified by tracking thorax and pelvis motion relative to global coordinates. Using an angle-angle plot of thorax and pelvis frontal plane rotation, a coefficient of determination (R^2) was calculated, where a high R^2 would indicate highly coupled thorax and pelvis motion and a low R^2 would indicate more dissociated or independent motion of the thorax and pelvis. This particular metric has been used during gait to distinguish participants with and without LBP through frontal and transverse plane trunk coupling,[7,52] and these types of intersegmental, intraindividual measures of motion have been suggested by other researchers.[56] Because the balance-dexterity task was performed in single-limb standing, it did not provide significant perturbations to the transverse plane but did provide these to the frontal plane. This was part of the a priori rationale for focusing on frontal plane motion, but motions and coupling in other planes were explored during pilot testing to fully characterize how the participants moved. There were no differences in transverse plane trunk coupling between the groups (P = .719). This was likely due to a ceiling effect, as almost all participants exhibited transverse plane coupling (R^2>0.9). More details on the frontal plane trunk coupling calculation and comparison to more traditional measures can be found in our previous work.[47] In addition, more traditional range-of-motion metrics were acquired, including trunk (thorax relative to pelvis), thorax, and pelvis angular excursions. Muscle activation data were averaged to acquire a mean activation amplitude for each trial. Muscle activation ratios were calculated in a frame-by-frame manner, including deep-to-superficial ratios for the paraspinals (LM/ES) and abdominals (IO/EO) and cocontraction ratios for the deep trunk muscles (LM and IO) and superficial trunk muscles (ES and EO), with the muscle of lower average amplitude in the numerator. Outliers were screened for aberrant or out-of-plane trunk motions during data collection and post hoc, and 1 such trial for 1 participant was removed. Mean trunk positions in all 3 planes during the balance-dexterity task were not near the end range of motion and were within about 10° of a neutral standing posture. Outcome variables were statistically analyzed using a 2-way analysis of variance and post hoc Bonferroni corrections when testing task (double-limb stance, single-limb stance, stable block, and balance-dexterity task) and group (control, recurrent LBP) main effects. Variables that were only analyzed in the balance-dexterity task condition were tested using paired t tests. Associations between outcome measures were tested by bivariate Pearson correlations, or by Spearman correlations in cases where normality or homoscedasticity was violated, with α = .05 for all tests (PASW Statistics; IBM Corporation, Armonk, NY).

RESULTS

Participants

Nineteen participants with recurrent LBP and no sign of neurological involvement and 19 matched back-healthy control participants participated in the study (**FIGURE 2**, **TABLE 1**). Participants with recurrent LBP were in symptom remission at the time of testing, with a mean VAS pain rating of 0.4 ± 0.4 out of 10. Assessment of social-cognitive factors with psychometric tools revealed that participants with recurrent LBP did

TABLE 1 Participant Demographics*

	Recurrent LBP (n = 19)	Controls (n = 19)	*P* Value
Age, y	23.5 ± 2.8	23.9 ± 3.3	.679
Sex, n			
Male	7	7	
Female	12	12	
Leg dominance, n			
Right	18	18	
Left	1	1	
Height, cm	170.4 ± 8.4	169.1 ± 10.4	.692
Weight, kg	68.7 ± 10.3	67.1 ± 10.8	.661
Body mass index, kg/m^2	23.6 ± 2.4	23.3 ± 1.8	.714
Baecke physical activity scale (vector sum)	4.8 ± 1.0	4.9 ± 0.6	.537
Episodes per year, n	3.4 ± 1.2		
Pain during episodes (recall; 0-10 VAS)	4.9 ± 2.2		
Pain at time of testing (0-10 VAS)	0.4 ± 0.4		
ODI (recall), %†	12 (6-16)		
PCS (0-52)†	5 (3-11)	6 (1-9)	.770
TSK (17-68)	31.3 ± 6.5	30.5 ± 6.0	.706
FABQ (0-96)	20.2 ± 10.7		
FABQ-PA (0-66)	12.2 ± 7.7		
FABQ-W (0-30)	8.1 ± 6.7		

Abbreviations: FABQ, Fear-Avoidance Beliefs Questionnaire; LBP, low back pain; ODI, Oswestry Disability Index; PA, physical activity subscale; PCS, Pain Catastrophizing Scale; TSK, Tampa Scale of Kinesiophobia; VAS, visual analog scale; W, work subscale.
**Values are mean ± SD unless otherwise indicated.*
†Values are median (first-third quartile range).

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not exhibit high levels of pain catastrophizing, fear avoidance, or kinesiophobia, and were not different in this respect from participants in the control group. One participant with recurrent LBP had missing LM and IO data due to a failed fine-wire electrode insertion.

Task Performance

Measures of balance and dexterous force control demands were not different between persons with recurrent LBP and back-healthy controls. All participants were able to complete the balance-dexterity task safely, with compression forces of 100 to 139 N (mean ± SD, 121.2 ± 12.3 N), representing 14.4% to 23.0% of body weight (mean ± SD, 18.7% ± 2.4%), for back-healthy controls and 102 to 159 N (mean ± SD, 123.5 ± 15.4 N), representing 13.8% to 22.2% of body weight (mean ± SD, 18.6% ± 2.7%), for persons with recurrent LBP (t_{18} = −0.544, P = .593, Cohen d = 0.125) (**FIGURES 3A** and **3B**). Nor were there differences between groups in self-report measures (.612>P>.452) (**FIGURE 3C**). Dexterous force control error, quantified as RMSE (t_{18} = −0.476, P = .640, Cohen d = 0.109) or CV (t_{18} = 0.011, P = .991, Cohen d = 0.003), was not different between groups (**FIGURES 4B** and **4C**). There was no significant task-by-group interaction effect for COP velocity ($F_{3,16}$ = 1.036, P = .403, η_p^2 = 0.163) or group main effect ($F_{1,16}$ = 0.416, P = .526, η_p^2 = 0.023), but there was a significant task main effect ($F_{3,16}$ = 152.525, P<.001, η_p^2 = 0.966). Center-of-pressure velocity increased from double-limb stance, to the stable-block condition, to single-limb stance and was greatest in the balance-dexterity task, and there were no group differences in any condition (**FIGURE 4A**). Task performance, therefore, was not affected by a history of recurrent LBP.

Trunk Control

Participants with recurrent LBP exhibited reduced frontal plane trunk coupling during the balance-dexterity task compared to control participants, with a moderate effect size (t_{18} = 2.457, P = .024, Cohen d = 0.564), but no differences in thorax (t_{18} = −1.058, P = .304, Cohen d = 0.243), pelvis (t_{18} = −1.414, P = .174, Cohen d = 0.324), or trunk frontal plane excursions (t_{18} = −1.333, P = .199, Cohen d = 0.306) (**FIGURE 5**). There were no associations between trunk coupling and COP velocity or dexterous force control RMSE or CV (**TABLE 2**). There were also no associations between trunk coupling and pain catastrophizing, kinesiophobia, or fear-avoidance beliefs (**TABLE 2**). For both groups, trunk coupling seemed to vary independently of balance and dexterous force control demands or social-cognitive factors, and persons with recurrent LBP exhibited reduced trunk coupling, that is, more dissociated motion of the thorax and pelvis.

Muscle activation data normalized to the stable-block condition revealed no significant differences in any individual

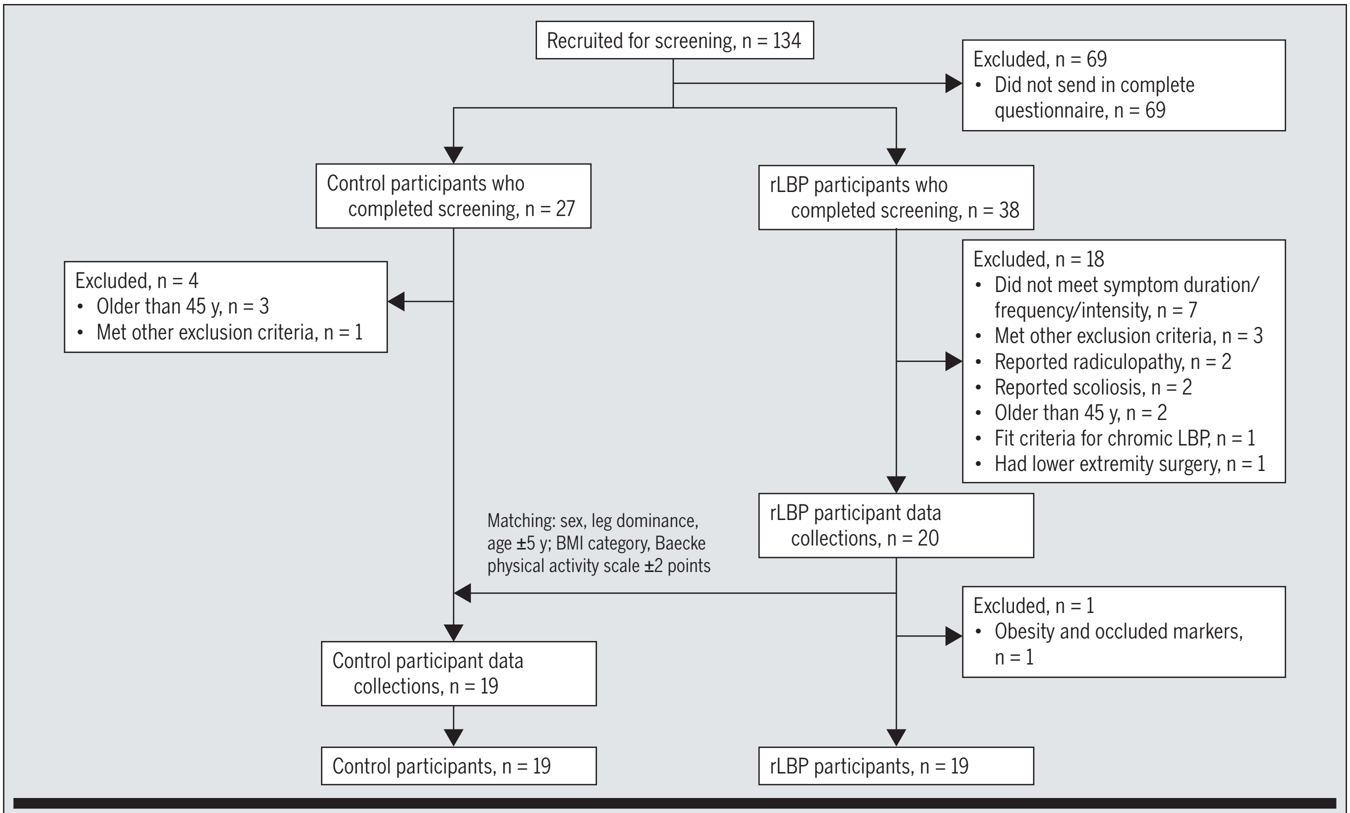

FIGURE 2. Participant recruitment. Abbreviations: BMI, body mass index; LBP, low back pain; rLBP, recurrent low back pain.

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EMG signal or ratio of EMG signals between groups (.972>P>.242) (**FIGURE 6**). No muscles alone were associated with trunk coupling, but ratios of deep-to-superficial paraspinals and abdominals were significantly positively associated with trunk coupling only in the recurrent LBP group (r = 0.618, P = .006 and r = 0.476, P = .046, respectively) (**FIGURE 7**). The same directional relationship was found in the back-healthy control group, but the association did not reach statistical significance. Greater deep trunk muscle (LM, IO) activation relative to more superficial trunk muscles (ES, EO) resulted in greater trunk coupling, while less relative deep muscle activation resulted in more dissociated thorax and pelvis frontal plane motion.

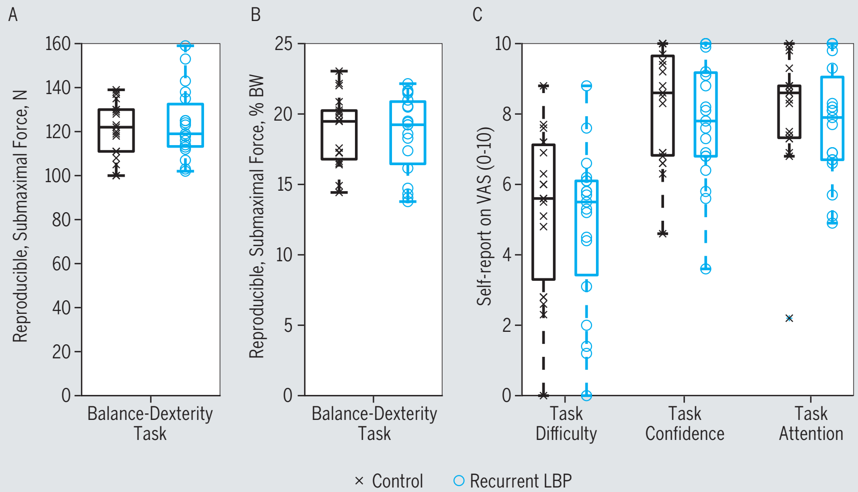

FIGURE 3. Reproducible, submaximal compression force achieved during practice trials and set as the goal for test trials of the balance-dexterity task, reported in (A) Newtons and (B) as a percentage of BW, and (C) self-report (VAS) measures of task difficulty, participant confidence, and the amount of attention required to complete the task (see Methods for VAS anchors) for persons with recurrent LBP and back-healthy control participants. Abbreviations: BW, body weight; LBP, low back pain; VAS, visual analog scale.

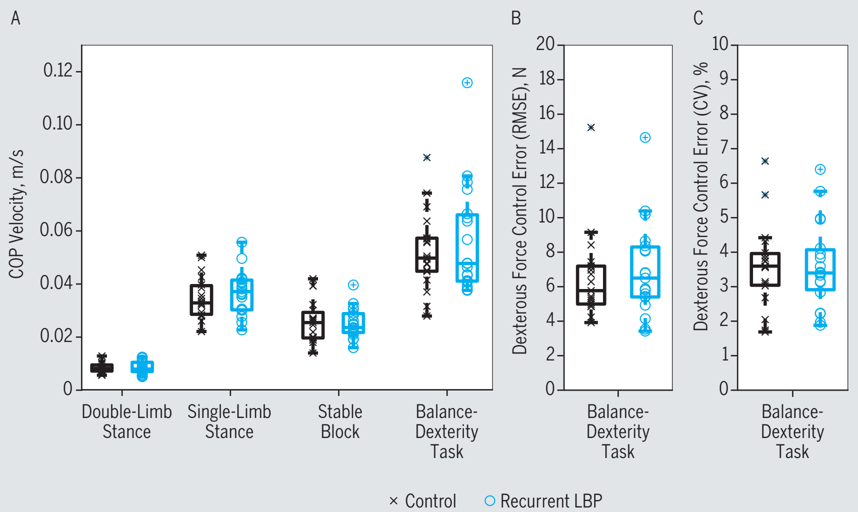

FIGURE 4. (A) The COP average resultant velocity magnitude in double-limb stance, single-limb stance, stable-block, and balance-dexterity task conditions, and dexterous force control measures, including (B) RMSE and (C) CV, of the vertical force produced in the balance-dexterity task for persons with recurrent LBP and back-healthy control participants. Abbreviations: COP, center of pressure; CV, coefficient of variation; LBP, low back pain; RMSE, root-mean-square error.

DISCUSSION

Persons with recurrent LBP had, on average, lower trunk coupling, indicating more dissociated thorax and pelvis motion, compared to back-healthy control participants. In the recurrent LBP group, trunk coupling was associated with deep-to-superficial paraspinal and abdominal EMG ratios, where greater deep muscle activation relative to more superficial muscles resulted in higher trunk coupling. In both groups, frontal plane trunk coupling varied independent of any task performance measure or psychometric measure collected. The a priori hypothesis was that a tight motor control strategy would be observed in the group of participants in remission from LBP. The movement data, however, did not support this hypothesis, and the muscle coordination findings further strengthened the lack of support. Conversely, the findings supported a loose motor control strategy, which may be the result of the low-demand, continuous, dynamically unstable balance-dexterity task, as well as the frontal plane analysis. Such a control strategy has been described in seminal work by Cholewicki and McGill,[5] where they suggested that low back symptoms could be triggered in low-demand tasks by instability and low back symptoms following a high-demand task could be related to tissue failure, both of which have been reflected more recently in commentaries.[55,56]

Performance on the balance-dexterity task did not distinguish between back-healthy persons and persons with recurrent LBP in symptom remission in the present study. Findings from previous research on standing balance tasks are mixed when it comes to differences between groups, but a majority of studies report greater COP sway measures in LBP groups.[9,38] This effect, however, is more robust for persons with symptomatic LBP, unlike in the present study. A recent

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attempt to use a clinical single-limb balance test to distinguish participants with and without chronic LBP identified reduced gluteus medius strength in the patient group; however, it did not translate to impaired single-limb stance.[42] Given these mixed findings, it is reasonable that no differences were observed in the present study for this group of young, minimally disabled persons in remission from recurrent LBP. A group of older participants with longer-duration or currently symptomatic LBP would potentially exhibit task performance differences. While task performance in our study sample was successful and measures of balance demands and dexterous force control were not distinguishable between groups, redundant control mechanisms allowed different trunk control strategies.

Counter to the hypothesis, no stiffening strategy was observed in the group with recurrent LBP. Coupling of frontal plane thorax and pelvis rotations was on average lower in persons with recurrent LBP, indicating more dissociated thorax and pelvis motion, while traditional trunk segment excursion measures were similar between groups. A few factors that may help to explain these findings are the influence of social-cognitive factors, the influence of current pain, and task difficulty. First, the unsupported hypothesis was built on investigations of discrete perturbations to posture where greater trunk cocontraction[30,44] and stiffness[21,53] were observed in persons with recurrent LBP. These perturbations, however, involved delivering external perturbing forces either to a support surface or directly to the trunk. This may invoke a stiffening strategy related to fear of movement or pain.[56] In fact, one study showed that persons with higher kinesiophobia and fear-avoidance beliefs exhibited greater trunk stiffness in one of these trunk-release tasks.[31] In the present study, there was no such association between trunk coupling and any psychometric measure of fear of pain or movement (**TABLE 2**). Next, populations studied in and out of pain exhibit mixed findings in continuous functional tasks. When performing a walking task while in pain, increased correlations of thorax and pelvis motion were observed,[13,52] but a study investigating the gait of persons in symptom remission showed no difference between groups.[7] A stiffening strategy may be more prevalent in persons currently in pain as opposed to those in symptom remission (the current study). Finally, task difficulty and especially trunk motion amplitude may help explain the lack of a stiffening response and the presence of dissociated trunk motion. The balance-dexterity task is a submaximal, low-range-of-motion, volitionally driven unstable balance task. It is likely that we are observing thorax and pelvis dissociation in this low-effort task, as opposed to the trunk stiffening we may have seen in other external perturbation paradigms or in higher-effort tasks. This

TABLE 2 ASSOCIATIONS BETWEEN TRUNK COUPLING AND TASK PERFORMANCE OUTCOME MEASURES AND PSYCHOMETRIC SCORES FOR PERSONS WITH RECURRENT LBP AND BACK-HEALTHY CONTROL PARTICIPANTS

	Recurrent LBP		Controls	
	Pearson *r*	*P* Value	Pearson *r*	*P* Value
Task performance outcome measures				
COP velocity, m/s	0.03	.92	0.26	.28
Dexterous force control: RMSE, N	0.16	.52	0.26	.28
Dexterous force control: CV, %	0.19	.43	0.15	.55
Psychometric scores				
PCS	–0.10	.68	0.07	.78
TSK	0.06	.80	–0.13	.59
FABQ	0.04	.87	...	...

Abbreviations: COP, center of pressure; CV, coefficient of variation; FABQ, Fear-Avoidance Beliefs Questionnaire; LBP, low back pain; PCS, Pain Catastrophizing Scale; RMSE, root-mean-square error; TSK, Tampa Scale of Kinesiophobia.

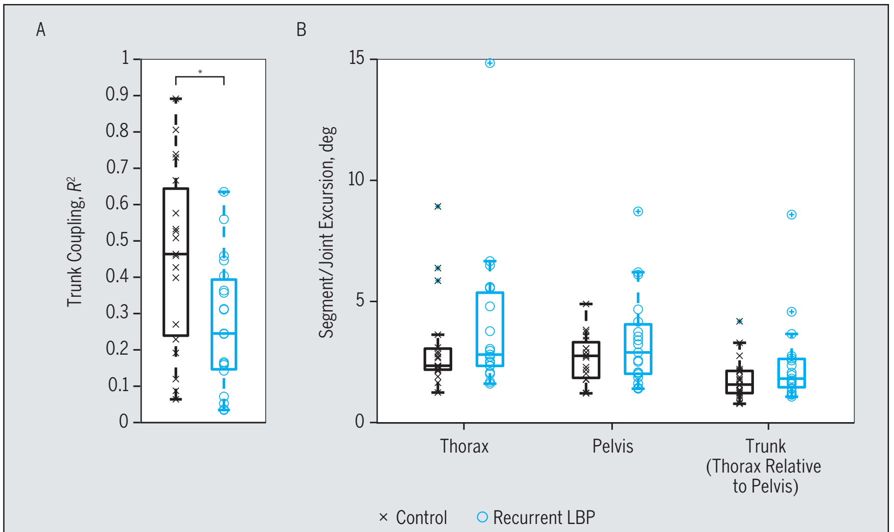

FIGURE 5. (A) Coupling of thorax and pelvis frontal plane rotation (trunk coupling; R^2) as well as (B) thorax, pelvis, and trunk frontal plane excursion during the balance-dexterity task in persons with recurrent LBP and back-healthy control participants. *$P<.05$. Abbreviation: LBP, low back pain.

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hearkens to a framework proposed by Cholewicki and McGill,[5] where causes of LBP in low-effort tasks are related to instability and in high-effort tasks are more related to tissue failure, as well as to more recent commentaries where "tight" and "loose" motor control strategies may be context dependent.[55] The balance-dexterity task serves as an unstable balance task to observe dissociated trunk motion in this population at one end of this continuum of task demands.

Our study supports a relationship between patterns of trunk coupling and deep trunk muscle dysfunction, as we observed associations between trunk coupling and deep-to-superficial trunk muscle ratios. Previous research has shown that persons with recurrent LBP exhibit dysfunction in deeper trunk muscles, most consistently the deep LM, transverse abdominis, and IO. The LM is atrophied at the level of pain[2] and has reduced metabolic measures.[19] In anticipation of voluntary arm movement, persons with recurrent LBP exhibit delayed activation of the deep LM[37] and transverse abdominis[24,26] in all directions of arm movement, and of the IO[24,26] in certain directions. Experimentally induced muscle pain through injection of hypertonic saline also reduced activity of the transverse abdominis and ES.[23] Though studied less frequently, perturbations through voluntary lower extremity movements show similar results of delayed activation of the transverse abdominis and LM consistently, and of the IO and ES depending on movement direction.[25,51] Mechanical modeling studies suggest that every trunk muscle contributes to lumbar stability in large and multiplanar movements, but that passive structures and the LM and ES primarily control stability in neutral-posture tasks with near-zero muscle forces.[5] Intra-abdominal pressure, a known contributor to lumbar spine stability and modulated through abdominal activation,[20] however, was not modeled in that study.[5] The relationships identified in the present study, where lower LM and IO activations were associated with lower trunk coupling, agree with previous investigations highlighting deep trunk muscle dysfunction and its relation to movement outcomes in populations in remission from LBP. We add here, however, that the activations of the deep trunk muscles relative to the more superficial trunk muscles were related to trunk coupling.

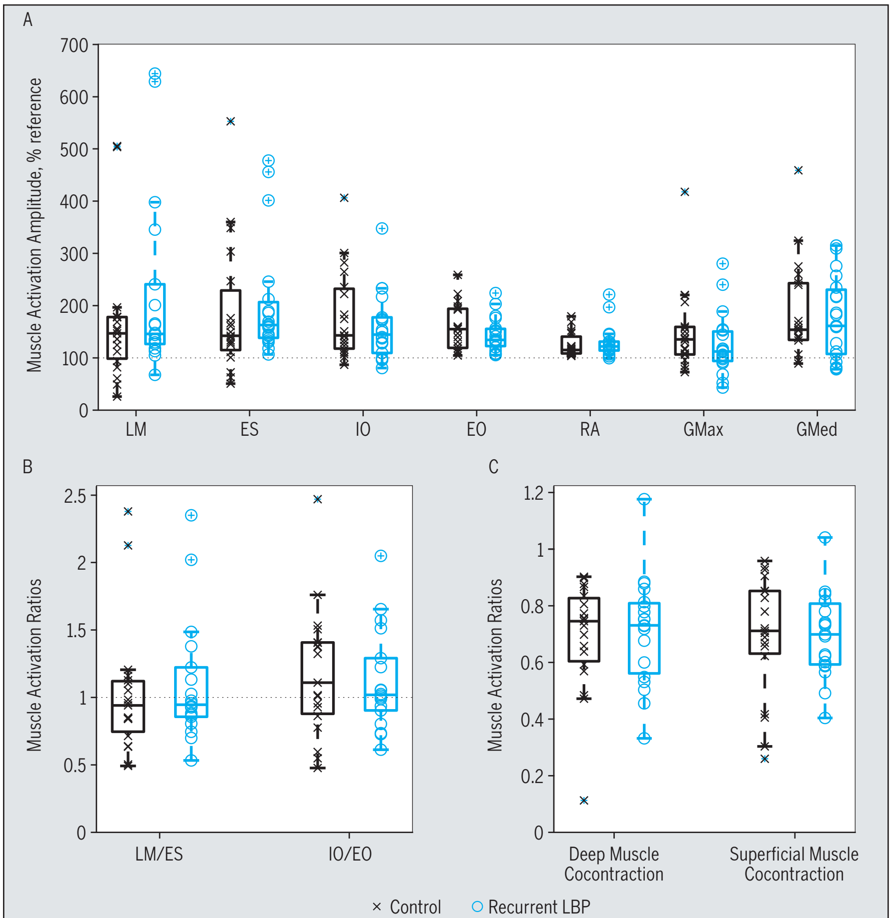

FIGURE 6. (A) Muscle activation data during the balance-dexterity task for the LM, ES, IO, EO, RA, GMax, and GMed. (B) Muscle activation ratios describing deep-to-superficial paraspinal activity (LM/ES) and deep-to-superficial abdominal activity (IO/EO). (C) Muscle activation ratios describing deep muscle cocontraction (LM and IO) and superficial muscle cocontraction (ES and EO) in persons with recurrent LBP and back-healthy control participants. Electromyography signals were normalized to the stable-block condition. Abbreviations: EO, external oblique; ES, erector spinae; GMax, gluteus maximus; GMed, gluteus medius; IO, internal oblique; LBP, low back pain; LM, lumbar multifidus; RA, rectus abdominis.

In the present study, the IO was operationally characterized as a deep trunk muscle in relation to the EO. While the authors acknowledge that the transverse abdominis is more often investigated as the deep abdominal muscle, we decided to use the IO as a surrogate to have greater confidence in the consistency and accuracy of our fine-wire electrode placement. There is experimental and anatomical research justifying the inclusion of the IO as a deep trunk muscle. In a study utilizing an unstable balance task similar in some ways to the balance-dexterity task, researchers found dysfunction in the IO as well as the transverse abdominis.[14] Anatomically, Vleeming et al[57] make a strong case for the role of the IO in stabilizing the lumbar spine through fascial connections to the paraspinal compartment and thoracolumbar fascia through the common tendon where both the IO and transverse abdominis, but not

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the EO, attach. We gain confidence in the relationship between the IO/EO ratio and trunk coupling because the same pattern was identified in the paraspinal musculature (LM/ES), and the IO was just one part of a comprehensive investigation into the effects of trunk muscle coordination on trunk coupling during the balance-dexterity task.

While we believe these relationships between trunk coupling and deep-to-superficial paraspinal and abdominal ratios to exist in both groups, statistical significance was only reached in the population in remission from recurrent LBP. Impaired motor control processes, including reduced trunk proprioception,[34,45] paraspinal atrophy,[2] and increased trunk extensor fatigability,[1] suggest that these individuals had less variability in trunk control strategies available to them, and so trunk coupling was more strongly, or more exclusively, influenced by muscle coordination. This is in contrast to back-healthy control participants, who have many redundant control mechanisms contributing to coupling. This supports hypotheses suggested in our previous work, where a back-healthy control group exhibited a weak association between the LM/ES ratio and trunk coupling, with signals normalized to maximum contractions.[47] Though the correlation between trunk muscle activation ratios and trunk coupling may not assist in decision making for an individual patient case, it may help to explain the observed decrease in trunk coupling in the group in remission from LBP and help to build testable hypotheses and interventions for future research. Focusing on the relative activation of deep and superficial trunk musculature in future research may help to reconcile variable findings in previous work, a suggestion highlighted by a recent commentary by van Dieën et al.[56]

The reduced trunk coupling associated with less relative deep trunk muscle activation has the capacity to contribute to lumbar spine degeneration and the recurrence of pain in this population. Dysfunctional mechanical behavior of the lumbar spine, through motor control dysfunction and/or tissue damage, is thought to play a role in degeneration[56] through intervertebral instability[3,5] or increased load and decreased movement variability.[22,27,54] Other groups have proposed a link between the stiffening strategy, characterized by increased superficial muscle activation and trunk stiffness, in persons with recurrent LBP and a reduction in movement variability leading to increased load of the same tissues. Here, we observed the opposite end of the spectrum: dissociated trunk motion suggesting reduced lumbar stability associated with reduced relative deep trunk muscle activity. There is evidence that in unstable tasks, overactive superficial trunk extensors can also contribute to trunk instability.[46,56] The balance-dexterity task itself may serve as a means to characterize these factors during patient assessment and rehabilitation of trunk control. Taking a closer look at individuals in **FIGURE 7** reveals that a few participants in both groups increased their deep-to-superficial trunk muscle ratios far above the mean in order to achieve trunk coupling similar to that of most back-healthy controls—consider 4 participants with an LM/ES ratio above 2.0 and 2 with an IO/EO ratio above 2.0. These individuals may represent one end of a continuum of how trunk muscle coordination influences trunk coupling during the balance-dexterity task. This continuum may be present in both groups and may be targeted for future subgroup analyses with a larger sample.

Limitations to generalizing and applying these findings must be considered. Participants made up a convenience sample of persons with and without recurrent LBP recruited from student groups, classes, flyers, and university-affiliated physical therapy clinics. Persons with recurrent LBP were generally young (mean ± SD age, 23.5 ± 2.8 years), minimally disabled (Oswestry Disability Index, 12.0%; interquartile range, 6%-16%), and all in pain remission at the time of testing (0.4 ± 0.4 out of 10 on the VAS). These findings should not be generalized to persons with recurrent LBP in a painful episode or persons with acute or chronic LBP. Also, this study defined LBP by anatomical location and did not attempt to categorize

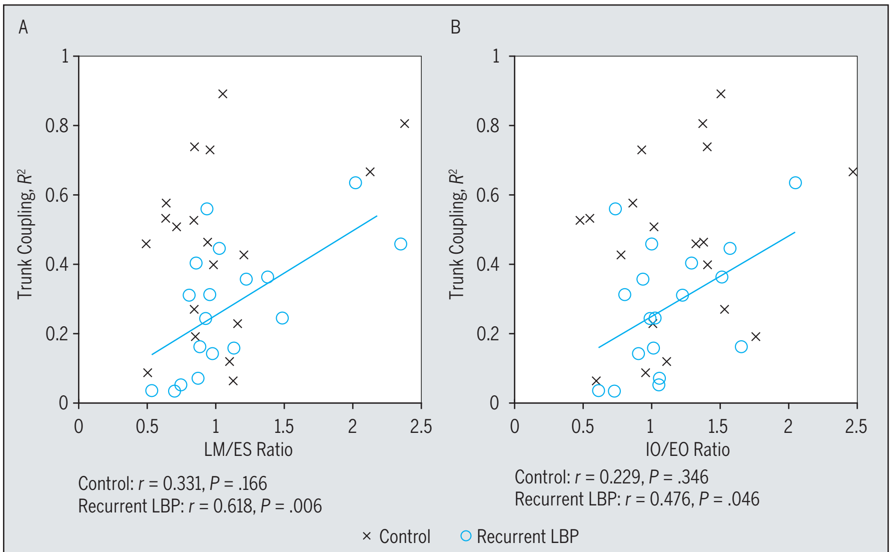

FIGURE 7. Associations between trunk coupling (R^2) and (A) the deep-to-superficial paraspinal muscle activation ratio (LM/ES) and (B) the abdominal muscle activation ratio (IO/EO) in persons with recurrent LBP and back-healthy control participants. Electromyography signals were normalized to the stable-block condition before the ratios were calculated. Abbreviations: EO, external oblique; ES, erector spinae; IO, internal oblique; LBP, low back pain; LM, lumbar multifidus.

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or classify the recurrent LBP participants into a more specific physical therapy diagnostic category. The usual limitations of EMG methodology apply here as well, including the potential for cross-talk from surface EMG and potential errors in fine-wire electrode placement. Insertions were done, however, under ultrasound guidance and confirmed through electrical stimulation, making substantial errors unlikely. Muscles were instrumented unilaterally due to limitations in the number of EMG channels available. This could lead to misleading interpretations of the findings, exemplified by recent investigations into bilateral transverse abdominis activation rebutting hypotheses that the muscle preactivates bilaterally and independent of perturbation direction.[39,40] Normalizing to the stable-block condition, however, helped to mitigate this potential confounding effect, as asymmetric forces from lifting the leg and pressing down on the block were removed in the normalization, so additional measured muscle activation reflected primarily effects of the added instability from the spring. Future work could also use a kinematic model with more resolution to identify motions and coupling of spinal regions, or even functional spinal units.

Future work should continue to examine the task dependency of what is commonly discussed about motor control dysfunction in persons with various LBP etiologies. Robust studies taking the same set of participants through a variety of controlled laboratory postural tasks—both externally perturbed and internally driven—will help elucidate the influence of postural demands, muscle coordination, and psychosocial factors on trunk control and pain recurrence in ecological or functional tasks of varying effort. Adding cognitive perturbations through dual-task interference can add to the ecological validity of the balance-dexterity task and may reveal how attentional demands influence trunk control and muscle coordination. Applied clinical research should also examine the effects of using the balance-dexterity task in patient assessment and rehabilitation.

CONCLUSION

PARTICIPANTS IN SYMPTOM REMISSION from recurrent LBP did not perform the balance-dexterity task differently from back-healthy controls, but exhibited reduced frontal plane trunk coupling, indicating more dissociated thorax and pelvis motion. In the participants with recurrent LBP only, lower trunk coupling was associated with lower deep-to-superficial paraspinal (LM/ES) and abdominal (IO/EO) muscle activation ratios. The balance-dexterity task is a submaximal, internally driven unstable balance task that induces sufficient perturbation to postural control to observe trunk control deficits in this minimally disabled population in remission from pain. ◉

KEY POINTS

FINDINGS: Persons with and without recurrent low back pain (LBP) performed similarly on the balance-dexterity task. Persons with recurrent LBP exhibited more dissociated trunk motion during the task than did back-healthy controls, which was related to reduced deep trunk muscle activity relative to more superficial trunk muscles.

IMPLICATIONS: The balance-dexterity task is a submaximal, internally driven unstable balance task during which more dissociated trunk motion, as opposed to the expected increased trunk stiffness, was observed in this minimally disabled population in remission from pain.

CAUTION: Findings underscore the task-dependent nature of trunk control research and assessment in persons with recurrent LBP, so generalizations to other tasks or presentations of LBP are not recommended.

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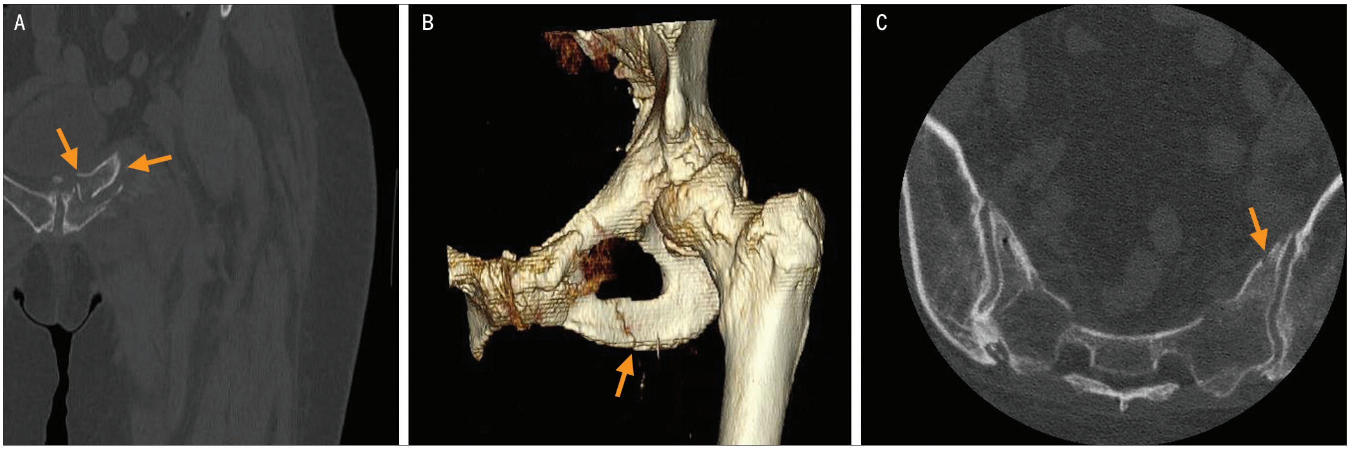

FIGURE. (A) Coronal computed tomography (CT) of the left hip demonstrating a comminuted, mildly displaced fracture of the left superior pubic ramus extending into the pubic symphysis; (B) 3-D CT of the left hip demonstrating a minimally displaced transverse fracture of the left inferior pubic ramus, and (C) axial CT of the lumbar spine at the level of the sacroiliac joint demonstrating a subtle nondisplaced fracture of the left sacral ala, likely extending into the left sacroiliac joint.

Pelvic Ring Fractures: Role of Physical Therapy in the Emergency Department

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An 87-year-old woman with a history of osteoporosis presented to the emergency department (ED) with complaints of low back pain and difficulty walking due to falling onto the deck of a cruise ship 2 weeks prior. She landed on her left hip, and, although she noticed immediate unilateral hip/groin and bilateral low back pain, she chose to continue traveling with limited, cane-assisted walking rather than return early. The medical staff aboard ship recommended ibuprofen and follow-up with her physician.

Upon returning home, she presented to the ED. Given the significant delay in diagnostic evaluation and persistent symptoms, computed tomography (CT) of the lumbar spine was ordered. The results of the CT were read as noncontributory, so the ED staff planned for discharge home. A physical therapist was consulted due to concerns regarding mobility safety and because the patient fulfilled the following fall-risk criteria: presented due to a fall, older than 65 years, and scored higher than 13.5 seconds on the timed up-and-go test.

Physical therapy examination revealed painful and limited range of motion and decreased strength of left hip flexion and internal rotation. Gait was antalgic and walker assisted; prior level of function included 3.2 km of independent walking daily. Based on examination findings and imaging guidelines, the physical therapist recommended left hip radiographs.[2,3] A CT scan of the hip was ordered due to its superior specificity in detecting subtle fractures and to assist intervention planning in the setting of geriatric trauma.[1] Imaging revealed 3 pelvic ring fractures (**FIGURE**). The orthopaedic service diagnosed the fractures as stable. The patient was discharged home, using a walker for ambulation, and referred to orthopaedics for follow-up care. Physical therapist evaluation within the ED reduced the likelihood of adverse events post discharge by expediting selection of appropriate intervention pathways. ◉ *J Orthop Sports Phys Ther 2019;49(12):942. doi:10.2519/jospt.2019.9093*

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Individuals With and Without Low Back Pain Use Different Motor Control Strategies to Achieve Spinal Stiffness During the Prone Instability Test

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Rehabilitation of patients with low back pain (LBP) by matching to treatment-based subgroups has been found to have superior outcomes compared to unmatched treatments.[3] Trunk stabilization exercise is one of the treatment classifications. Interventions for this subgroup are believed to address muscle coordination impairments in patients with spinal instabilities.[12,19,24,30] Individuals with LBP are theorized to have impairments in ligamentous or bony structures of the spine, resulting in increased spinal segment mobility and a reduction in spinal stability, or the ability to resist deformation (changes in spinal alignment or curvature) during forces applied on the spine.[32,33] Trunk muscle recruitment is believed to augment spinal stability during forces applied to the spine.[16,31]

BACKGROUND: The prone instability test is used to identify individuals with low back pain (LBP) who would benefit from trunk stabilization exercises. Although activity from muscles during the leg-raising portion of the prone instability test theoretically enhances spinal stiffness and reduces pain, evidence for this is lacking.

OBJECTIVES: To compare and contrast (1) pain and stiffness changes between prone instability testing positions, and (2) muscle activation patterns during the prone instability test leg raise in individuals with and without LBP.

METHODS: Participants with (n = 10) and without (n = 10) LBP participated in this laboratory case-control study. Spinal stiffness was measured using a beam-bending model and 3-D kinematic data. Stiffness changes were compared across the test positions and between groups. Surface electromyographic data were collected on trunk and limb musculature. Principal-component analysis was used to extract muscle synergies.

RESULTS: Spinal stiffness increased across testing positions in all participants ($P<.05$). Participants with LBP experienced reduced pain during the test ($P<.001$). No between-group difference was found in spinal stiffness during leg raising during the test ($P>.05$). Participants without LBP used 3 muscle synergies during the leg raise and participants with LBP used 2 muscle synergies.

CONCLUSION: Spinal stiffness increased in all participants; however, participants without LBP demonstrated a muscle synergy pattern where each synergy was associated with a distinct function of the prone instability test. Participants with LBP used a more global stabilization pattern, which may reflect a maladaptive method of enhancing spinal stability. *J Orthop Sports Phys Ther 2019;49(12):899-907. Epub 3 Aug 2019. doi:10.2519/jospt.2019.8577*

KEY WORDS: *clinical test, EMG, lumbar, movement coordination*

The prone instability test (PIT) identifies individuals with LBP who would benefit from trunk stabilization exercise.[19,34] The test is performed with patients in prone, with their legs over the end of a treatment table. The clinician applies a posterior-to-anterior (PA) force on the lumbar spine to provoke pain. If pain is provoked, then the patient extends both hips, and force is reapplied. Pain reduction with leg raising, theoretically resulting from muscle-enhanced stability, is considered a positive test.[16,23,31,47] However, spinal stiffness change and muscle activation during this test are unknown.

Lumbar extensor contractions between 30% and 50% of maximal volitional contraction can increase spinal stiffness.[9,35,37] Hip extension has demonstrated lumbar erector spinae activation between 60% and 80% of maximal volitional contraction, but the role of the lumbar multifidus, which contributes up to two thirds of lumbar spine stability, was not described.[2,49] Individuals with LBP predicted to benefit from trunk stabilization exercises via a positive PIT have demonstrated lumbar multifidus

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activation impairments.[17] Individuals with LBP have demonstrated altered muscle activation patterns and muscle onset timing when compared to healthy participants.[7,36,43,44] Elucidating the impact of impaired lumbar multifidus function on motor performance during a PIT would enhance the current body of knowledge related to motor control in patients with LBP. Comparison of lumbopelvic activation patterns between individuals with and without LBP may also provide better understanding of mechanisms underlying the PIT, enhancing examination and intervention planning for patients. Furthermore, little is known about limb muscle activation of the latissimus dorsi and gluteal muscles, which can aid spinal stability through anatomical attachments, during the PIT.

Our purpose was to characterize spinal stiffness changes and lumbopelvic muscle activation patterns during the PIT in participants with and without LBP. We hypothesized that, due to changes in spinal position and muscle activation, all participants would increase spinal stiffness under a PA force to the lumbar spine when progressing from a resting prone position to the leg raise of the PIT. We also hypothesized that individuals with LBP would have altered muscle synergies and decreased activation of the lumbar multifidus during the PIT, even with a positive test. Inclusion of individuals without LBP provided comparison of the characteristics of spinal stiffness and muscle activation to those of individuals with LBP.

METHODS

Participants

Spinal stiffness and muscle activation were compared via case-control design. We recruited 10 individuals with and 10 without LBP between the ages of 18 and 45 years from September 2015 through December 2016. All participants provided informed written consent approved by Drexel University's Institutional Review Board. Individuals with LBP were included if they had current LBP that was less than 6 months in duration, required consultation with a health care provider, or resulted in self-limiting regular activity and function. Patients were excluded based on factors reported in their history and upon physical examination by a licensed physical therapist (**TABLE 1**). Individuals with LBP completed the Oswestry Disability Index[15] and the Fear-Avoidance Beliefs Questionnaire.[46] Participants without LBP included individuals with no history of LBP that required medical intervention or limited their activity for longer than 3 days. **TABLE 2** contains participant demographics.

A pilot study investigating spinal stiffness change between the resting position and leg-raise portion of the PIT within 5 individuals with LBP revealed an effect size of d = 2.14. Power analysis determined that 4 participants were necessary to detect a difference in stiffness within participants with LBP between the PIT positions (paired t test, α = .05, β = .80). Because individuals without LBP were included in the study cohort, the sample size was doubled to allow for increased variance and the potential that the effect would not be as large in those individuals.

Instrumentation

Kinematic data were collected from the pelvis (S2) and lumbar spine (L1) at 120 Hz using an electromagnetic tracking system (LIBERTY; Polhemus, Colchester, VT) and used to measure spinal stiffness. Surface electromyographic (EMG) data were collected at 2400 Hz (gain, 500; band-pass filtered at 20-750 Hz; SA Instrumentation Company, San Diego, CA) from the external oblique, lumbar mul-

TABLE 1 EXCLUSION CRITERIA FOR PARTICIPANTS WITH LOW BACK PAIN

Reported Patient History	Physical Examination
Spinal fracture	Body mass index greater than 30 kg/m^2
Spinal or hip surgery	Weakness in myotomal distribution
Osteoporosis	Presence of Babinski reflex
Active inflammatory joint disease	Spasticity
Signs of systemic illness (spinal tumor, cancer, infection)	Leg-length discrepancy greater than 2.5 cm
History of rehabilitation with return to function and no recurrence	Visibly observable spinal curvature of the frontal plane (scoliosis)
Pain or paresthesia below the knee	Lateral lumbar shift

TABLE 2 PARTICIPANT DEMOGRAPHICS*

	LBP Group (n = 10)	Control Group (n = 10)
Sex, n		
Female	8	5
Male	2	5
Age, y	28.8 ± 3.1	28.5 ± 5.9
Body mass index, kg/m^2	23.5 ± 1.4	22.6 ± 2.3
Trunk length, cm	50.8 ± 3.8	55.1 ± 4.2
Skin thickness over L4-L5, mm	6 ± 2	6 ± 2
FABQ-physical activity	2.9 ± 3.9	...
Oswestry Disability Index	17.4 ± 17.1	...

Abbreviations: FABQ, Fear-Avoidance Beliefs Questionnaire; LBP, low back pain.
**Values are mean ± SD unless otherwise indicated.*

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tifidus, lumbar erector spinae, thoracic erector spinae, latissimus dorsi, gluteus maximus, and hamstring muscles bilaterally using Ag/AgCl electrode pairs with a 2-cm interelectrode distance (**TABLE 3**).[26,28]

While lumbar multifidus data cannot be collected with surface EMG electrodes at the L3 level, surface electrodes at L5 have been reported to represent lumbar multifidus activity in several studies.[1,10,13,14,27,39] Cadaveric exploration in our lab demonstrated that the L4-S1 region consists predominantly of the lumbar multifidus muscle belly, with only nonexcitable tendons of the erector spinae. Additional work with L5 electrode placements in 10 healthy participants resulted in an average of 24% cross-talk (95% confidence interval: 17%, 30%) between the lumbar multifidus and erector spinae during isometric trunk extension.[25] Cross-talk of less than 30% suggested the ability to determine activity across different muscles.[45] Therefore, we were confident that the activity at the L5 electrodes represented the lumbar multifidus.

Electromyographic data were processed by removing heart rate artifact via independent-component analysis.[4] Data were rectified (root-mean-square; time constant, 30 milliseconds), and the resting EMG signal was subtracted through a custom LabVIEW program (Version 8.6; National Instruments, Austin, TX). Adipose tissue filtering of the EMG signal was controlled by using body mass index as an exclusion criterion. Skin thickness was measured using a skin-fold caliper (JLW Instruments, Chicago, IL) at L4-L5, with no difference in skin thickness between groups ensuring adipose tissue parity.

Posterior-to-anterior force (Newtons) was applied to the spinous processes of participants using a uniaxial 22.7-kg compression load cell (Transducer Techniques, LLC, Temecula, CA) mounted to a handle. The apparatus allowed force application to the spinous process in alignment with the kinematic sensors (Polhemus) located between L1 and S2 (**FIGURE 1**). Force data collected at 2400 Hz were visually streamed in real time to the tester, ensuring similar forces during testing. Tester rate of force application calculated across conditions and participants revealed a 3.7% coefficient of variation. Participants indicated pain during testing via an event trigger that created a time stamp indicating a pain-provoking force. All data sources were collected simultaneously during testing. Electromyographic, force, and event trigger data were downsampled to 120 Hz and time synchronized to the kinematic data.

Procedures

Electromyographic electrodes were applied and 2 trials of resting EMG (30-second duration) were collected in sitting. Two break-test trials of the modified Biering-Sørensen test, unilateral bridge, abdominal curl-up, and bilateral shoulder extension were used to obtain maximal voluntary isometric contractions (MVICs). The modified Biering-Sørensen test was performed with the participant in prone on a table, with the pelvis and

TABLE 3 Surface Electrode Placements for Electromyography

Muscle	Location
Gluteus maximus	Midpoint between the lateral edge of the sacrum and greater trochanter
Hamstrings	15 cm from the ischial tuberosity
Lumbar multifidus	2 cm lateral to the L5 spinous process
External oblique	15 cm lateral to the umbilicus
Thoracic erector spinae	5 cm lateral to the T9 spinous process
Lumbar erector spinae	3 cm lateral to the L2 spinous process
Latissimus dorsi	Midline between the T9 spinous process and axillary line

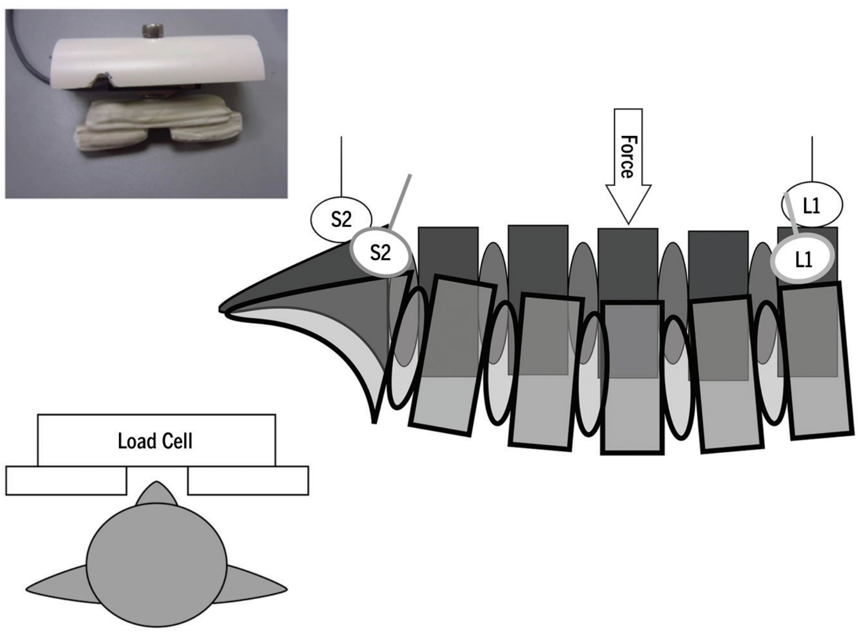

FIGURE 1. Setup for kinematic sensors over the L1 and S2 spinous processes, along with the location of the posterior-to-anterior compression force (arrow) relative to the sensors. The illustration depicts the angle change of the L1 kinematic sensor with respect to the S2 sensor during application of the posterior-to-anterior force used to calculate spine stiffness. The inset is a photograph of the load cell adapted to allow the tester to apply posterior-to-anterior force over the spinous process. A schematic to demonstrate the orientation of the load cell with respect to the vertebral body is also shown.

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lower extremity secured. The head of the table was lowered and the participant was required to maintain the trunk parallel to the floor. Kinematic sensors were then placed at L1 and S2, followed by testing. A physical therapist with 14 years of clinical experience in spinal rehabilitation performed all testing.

Stiffness Testing: Prone Baseline measures of spinal stiffness and pain were collected in prone (**FIGURE 2A**). To standardize force during all testing for participants with LBP, a PA force was applied to the spinous processes of L2 through L5 until they signaled pain production or an increase in current pain. Force was held steady for 2 seconds following the participant's indication of pain. The pain-provoking force was used as a visually displayed force target provided to the tester for the remaining conditions throughout the study. Participants were asked to rate their pain from 0 to 10 on the numeric pain-rating scale (NPRS; 0 is no pain and 10 is the worst possible pain).[5] Participants then underwent 2 trials of pain-producing force application to the most painful segment, separated by a 2-minute rest period. The tester collected the force applied in real time, along with the force target (±2.5% boundary). The force for participants without LBP was standardized to 22 N, based on pilot work that identified 22 N as the average pain-provoking force in individuals with LBP. Force was applied at L3 due to its midpoint on the lumbar spine.

Stiffness Testing: PIT Starting Position After identifying the pain-generating force and segment in prone, participants were placed in the starting position of the test (**FIGURE 2B**). Participants placed their arms overhead, with their feet resting on the floor with the knees extended. Force was applied for 2 seconds to the painful segment identified in prone, with participants signaling pain and providing NPRS ratings. Two trials were performed, with a 2-minute rest between trials.

Stiffness Testing: PIT Leg Raising A 61-cm-high beam was placed above the participants' calves. Participants held the table and raised their legs to the height of the beam, with knees extended (**FIGURE 2C**). Force was applied to the same lumbar segment previously identified for 2 seconds, with participants signaling pain and providing NPRS ratings. Two trials were performed. Participants also underwent 1 trial of the maximum tolerated force (the maximum force able to be produced by the tester in participants without LBP). This step was included because there is no clear instruction on the amount of force applied to the spine during clinical testing of the PIT.

Data Reduction and Statistical Analysis

Clinical Results Pain and force applied were normally distributed (Kolmogorov-Smirnov test; P>.05). Pain levels between PIT positions in participants with LBP were averaged between the trials and compared using paired t tests (α = .05). Forces applied during testing were averaged across trials by position and compared between groups via independent t tests (α = .05).

Spine Stiffness An elastic beam model was used to calculate lumbar bending stiffness during the application of the PA force.

$$EI = \frac{\int_{XL1}^{Xs} M dx}{\theta_{L1S}}$$

Bending stiffness (EI) between the sacrum (S) and L1 is expressed by the moment along the area divided by the angular deformation between S and L1 (θ_{L1S}) as force was applied.[22] Bending compliance of the spine was represented by a slope of the force (y-axis) against the angle change (x-axis) and expressed in Newton meters per degree, with the inverse reflecting stiffness. Force versus angle plots in prone revealed a linear line of best fit for the data, with a median R^2 of 0.96 (range, 0.75-0.99). Our technique demonstrated good agreement when tested against objects with known stiffness values. Within-day reliability spinal stiffness measures were assessed in 5 individuals with LBP in prone (intraclass correlation coefficient [ICC]$_{2,1}$ = 0.90; standard error of measurement [SEM], 2.1 Nm/deg^{-1}), at the PIT starting position (ICC$_{2,1}$ = 0.79; SEM, 4.7 Nm/deg^{-1}), and during the leg raise (ICC$_{2,1}$ = 0.95; SEM, 1.01 Nm/deg^{-1}).

Stiffness Comparison Stiffness trials were averaged within each condition. Friedman analysis of variance was used to compare spinal stiffness within groups between the conditions of prone, starting position of the PIT, leg raising, and leg raising with application of maximal force (α = .05), due to nonnormal distribution (Kolmogorov-Smirnov test; P<.05). Post hoc comparisons were made within groups for spinal stiffness against force in prone versus the starting position and

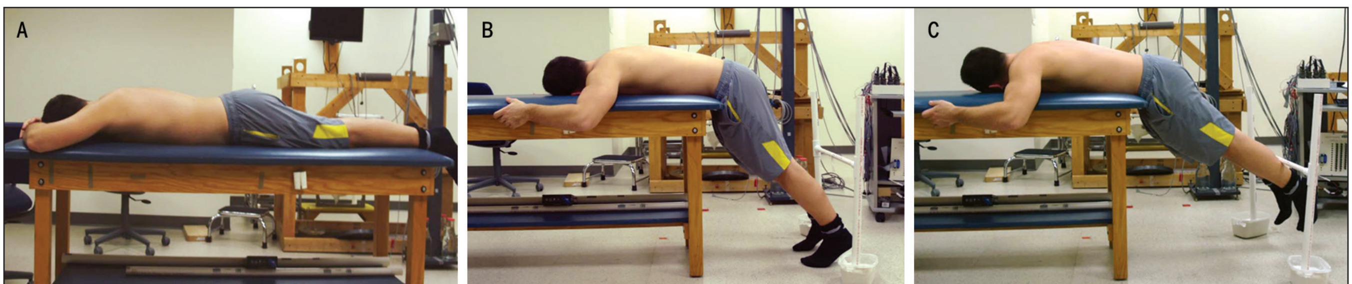

FIGURE 2. Prone instability test positions for collection of pain and spinal stiffness. (A) Relaxed prone, (B) starting position, and (C) leg-raise position.

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for the starting position versus leg raising, along with leg raising with force versus application of maximal force, using the Wilcoxon signed-rank test (α = .05). Effect size was calculated as $r = Z/(\sqrt{N_x + N_y})$, where $N_x + N_y$ is the number of observations.

Spinal stiffness percent change [(final value – initial value)/initial value × 100] was used to compare spinal stiffness between groups. Mann-Whitney U tests were used to compare stiffness percent change between groups (1) from prone to the PIT starting position and (2) from the starting position to leg raising (α = .05), due to nonnormal distribution (Kolmogorov-Smirnov test; P<.05). Effect size was calculated as $r = Z/\sqrt{N}$, where N is the number of cases. Effect size was interpreted as small (r = 0.10), moderate (r = 0.30), or large (r = 0.50).[8] All comparisons were performed using SPSS Version 21 (IBM Corporation, Armonk, NY).

Muscle Activation With Leg Raise A 2-second window of the root-mean-square EMG time series (MVIC normalized) from the point of force application during leg raising was entered into a principal-component analysis to determine whether individuals with LBP had altered muscle activation patterns during the PIT. Principal-component analysis can identify synergy patterns controlling movement.[20,21] Each synergy is presumed to be controlled by a single neural command from the central nervous system, modulating the overall magnitude of the synergy patterns. This approach allows characterization of a small number of synergies controlling the lumbopelvic complex during the PIT. That same EMG window was averaged for the lumbar multifidus and erector spinae in participants with LBP to identify activation magnitude. The data were averaged by side, as there were no significant side-to-side differences (P>.05) across muscles and averaged trials. Activation magnitudes were compared between participants with and without LBP using individual Mann-Whitney U tests (α = .05), with effect size (r) calculated as described previously due to nonnormal distribution (Kolmogorov-Smirnov test; P<.05).

RESULTS

Clinical Results

No participant without LBP demonstrated pain during the PIT. Nine of 10 participants with LBP had pain provocation in the prone position. All 9 of these participants had a positive PIT (reduction in provoked pain with leg raising). **TABLE 4** lists the applied forces (Newtons) and pain levels (NPRS) between the test positions. No significant differences were found in PA force between participants with and without LBP (P = .399). Participants with LBP had significantly less pain with PA force during the leg raise compared to both the prone (P<.001) and starting positions of the PIT (P<.001). There was no significant difference in pain between the prone and starting positions of the test (P = .611).

Spinal Stiffness

There was a significant difference in spinal stiffness between the positions of the PIT in participants with LBP ($\chi^2(3)$ = 21, P<.001). **TABLE 5** contains descriptive statistics (median, lower quartile [Q1], and upper quartile [Q3]) for these comparisons. Post hoc analysis revealed significantly greater spinal stiffness between the prone and starting positions of the PIT (P = .007, r = 0.60). There was also a signifi-

TABLE 4 Force Applied and Pain Intensity Produced During the Prone Instability Test Conditions*

	Control Group	LBP Group
Force, N†	22.0 ± 0	24.4 ± 8.8
Leg-raise maximal force, N†	41.1 ± 13	42.1 ± 12.9
Pain in prone‡	0 ± 0	4.6 ± 2
Pain in starting position‡	0 ± 0	4.1 ± 1.7
Pain during leg raise‡	...	0.3 ± 0.7
Pain during leg raise: maximal loading‡	...	0.6 ± 1.4

Abbreviation: LBP, low back pain.
**Values are mean ± SD.*
†The same applied force was used across conditions (prone, starting position, and leg raising) of the prone instability test. There was no difference in the force applied during maximal loading during leg raising between participants without LBP (control group) and those with LBP.
‡Pain was measured with the numeric pain-rating scale (0-10).

TABLE 5 Lumbar Spine Stiffness Against a Posterior-to-Anterior Force During the Prone Instability Test*

Position	Control Group	LBP Group
Prone	12.7 (8.7-17.2)	5.6 (4.6-7.5)†
Starting position	12.8 (9.2-18.2)‡	13.5 (9.6-16.6)†§
Leg raise	46.8 (17.7-57.8)‡	22.1 (16.8-28.6)§
Leg raise with application of maximal force	33.5 (17.7-44.2)	21.3 (11.7-39.1)

Abbreviation: LBP, low back pain.
**Values are median (lower quartile-upper quartile) Newton meters · degrees. There were significant between-group differences for all test positions.*
†The LBP group had significantly greater stiffness when transitioning from prone to the starting position.
‡The control group had significantly greater stiffness between the starting position and the leg-raise portion of the prone instability test.
§The LBP group demonstrated significantly greater stiffness between the leg-raise portion of the prone instability test and the starting position of the test.

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cant increase in spinal stiffness from the starting position to the leg-raise portion of the PIT during force application (P = .007, r = 0.60). There was no significant difference in stiffness between the leg raise with application of the pain-provoking force and application of maximal force (P = .646, r = 0.10).

Participants without LBP also demonstrated a significant increase in spinal stiffness between the positions of the PIT ($\chi^2(3)$ = 12.4, P = .007). Post hoc analysis revealed no difference in spinal stiffness between the prone and starting positions of the PIT (P = .799, r = 0.05). There was a significant increase in spinal stiffness from the starting position to the leg-raise portion of the PIT with application of the standard 22-N force (P = .007, r = 0.60). There was no significant difference between the leg raise with application of the 22-N force and application of maximal force (P = .169, r = 0.24).

There was a significant difference between groups in the stiffness percent change from prone to the PIT starting position. Participants without LBP (median, 20.8%; Q1-Q3, 14.2%-60.9%) demonstrated a smaller stiffness change above baseline than did those with LBP (median, 120.5%; Q1-Q3, 69.8%-211.9%; P = .004, r = 0.63). There was no significant difference in the stiffness percent change from the PIT starting position to the leg raise between participants without LBP (median, 106.3%; Q1-Q3, 60.9%-290.5%) and with LBP (median, 54.5%; Q1-Q3, 25.7%-134.9%; P = .123, r = 0.35).

Post hoc analysis of the normalized EMG amplitude averaged across 2 trials was explored within the LBP group due to the significantly smaller stiffness change in participants without LBP between the prone and PIT starting positions. Wilcoxon signed-rank tests (α = .05) performed separately for the external oblique, latissimus dorsi, thoracic and lumbar erector spinae, lumbar multifidus, gluteus maximus, and hamstrings demonstrated no significant muscle activation difference between the prone and PIT starting positions. **TABLE 6** contains the median muscle activation values and P values.

Muscle Activation Patterns and Amplitude With Leg Raise

Participants Without LBP Time-series EMG pattern analysis yielded 3 muscle synergies, accounting for 93.2% of the variance during leg raising (Bartlett's test statistic, 0.006). The first synergy accounted for 41.8% of the variance and included the latissimus dorsi, lumbar erector spinae, and lumbar multifidus. The second synergy comprised the thoracic erector spinae and gluteus maximus and accounted for 31.7% of the variance. The third synergy was represented by the hamstrings and accounted for 19.7% of the variance.

Participants With LBP Pattern analysis yielded just 2 muscle synergies, accounting for 77.3% of the variance during the

TABLE 6 ELECTROMYOGRAPHIC ACTIVATION DURING THE PRONE AND STARTING POSITIONS OF THE PRONE INSTABILITY TEST FOR PARTICIPANTS WITH LOW BACK PAIN*

Muscle	Prone	Starting Position	*P* Value
External oblique	1 (0-15)	1 (1-9)	.60
Thoracic erector spinae	0 (0-3)	1 (0-12)	.068
Latissimus dorsi	1 (1-4)	3 (1-6)	.116
Lumbar erector spinae	0 (0-1)	1 (0-3)	.225
Lumbar multifidus	0 (0-2)	4 (0-8)	.345
Gluteus maximus	1 (0-3)	1 (0-9)	.345
Hamstrings	1 (0-9)	1 (0-9)	.249

**Values are median (lower quartile-upper quartile) percent.*

TABLE 7 MUSCLE SYNERGIES EXTRACTED USING PRINCIPAL-COMPONENT ANALYSIS, WITH MATRIX CORRELATION VALUES FOR MUSCLES AND VAF FOR EACH SYNERGY*

	Muscle					
	LD	LES	LM	TES	GM	HS
Control group						
Synergy 1 (41.8% VAF)						
Matrix correlation	0.98	0.93	0.73			
Synergy 2 (31.7% VAF)						
Matrix correlation				0.92	0.93	
Synergy 3 (19.7% VAF)						
Matrix correlation						0.98
LBP group						
Synergy 1 (56.8% VAF)						
Matrix correlation	0.73			0.91		0.89
Synergy 2 (20.5% VAF)						
Matrix correlation		0.77	0.94		0.95	

Abbreviations: GM, gluteus maximus; HS, hamstrings; LBP, low back pain; LD, latissimus dorsi; LES, lumbar erector spinae; LM, lumbar multifidus; TES, thoracic erector spinae; VAF, variance accounted for.
**The external oblique was included in the analysis but did not load onto any synergy.*

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leg raise (Bartlett's test statistic, 0.048). The first synergy comprised the thoracic erector spinae, latissimus dorsi, and hamstrings and accounted for 56.8% of the variance. The second synergy comprised the lumbar erector spinae, lumbar multifidus, and gluteus maximus and accounted for 20.5% of the variance (**TABLE 7**).

Lumbar multifidus activation (percent MVIC) was significantly greater in participants without LBP (median, 58%; Q1-Q3, 51%-79%) during the leg-raise portion of the PIT compared to those with LBP (median, 40%; Q1-Q3, 31%-58%; $P = .015$, $r = 0.54$). Lumbar erector spinae activity was also significantly greater in participants without LBP (median, 61%; Q1-Q3, 52%-81%) compared to those with LBP (median, 33%; Q1-Q3, 31%-54%; $P = .023$, $r = 0.52$).

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DISCUSSION

The PIT is used to assist in identifying patients who would benefit from trunk stabilization exercises. Our results support that the test can identify individuals with the ability to increase spinal stiffness through recruitment of spinal musculature. Participants with LBP demonstrated pain reduction and increased spinal stiffness during the test. However, when compared to participants without LBP, the LBP group demonstrated an altered muscle recruitment strategy to increase spinal stiffness. Participants with LBP preferred global stabilizers to intrinsic spinal stabilizers, in contrast to participants without LBP.

Spinal Stiffness Changes During the PIT

Spinal stiffness increased across both groups during the PIT, with values exceeding the SEM. The LBP group also demonstrated a significant reduction in pain during the leg raise. However, 1 participant with LBP did not have pain reproduction during testing (negative result). A negative PIT response reduces the likelihood that a patient would benefit from trunk stabilization exercises.[19,34] This finding could be expected, as a cross-sectional study identified that only 17% of enrolled patients fit into the trunk stabilization group.[38]

Participants with LBP experienced pain in the prone and starting positions of the test. However, stiffness increased significantly between these positions, without differences in muscle activity. The starting position of the test may place tension across passive structures, resulting in increased spinal stiffness. Excessive spinal flexion in the starting position may potentially increase stiffness enough to prevent pain production, resulting in a false-negative test result.

Muscle Synergies and Level of Activation During the PIT

Muscle groups were represented across different synergies and accounted for different proportions of the total variance. Muscles within a component are considered to be acting in unison to contribute to the total synergy.[48] Participants without LBP had 3 synergies that explained 93.2% of the activation variance. The first component comprised the latissimus dorsi, lumbar erector spinae, and lumbar multifidus and explained the majority of the variance and the primary lumbar stabilizing strategy. The latissimus dorsi has an attachment to the spine via the thoracolumbar fascia, while the lumbar multifidus and erector spinae have a bone-tendon interface with the lumbar spine and are considered intrinsic stabilizers.[6] The lumbar multifidus and erector spinae are likely stabilizing the lumbar spine. The latissimus dorsi may be maintaining trunk position on the table while providing some contribution to lumbar spine stability through the fascia. The second synergy included the thoracic erector spinae and gluteus maximus and may be associated with stabilizing the thoracic spine and pelvis, respectively, during leg raising.[11] The posterior pelvic tilt moment created by the gluteus maximus when raising the feet off the ground[29] may require the thoracic erector spinae to counterbalance that action. The gluteus maximus may also be coupling with the thoracic erector spinae to provide global stabilization during movement. However, this global stabilization appears to play a smaller role, based on the smaller variance accounted for by the second synergy. The hamstrings in the third component are likely responsible for extending the hip.

Two synergies were extracted by principal-component analysis in participants with LBP. The first synergy consisted of the thoracic erector spinae, latissimus dorsi, and hamstrings and accounted for a majority of the variance during the leg raise. The second synergy of the lumbar multifidus, lumbar erector spinae, and gluteus maximus only accounted for 20.5% of the variance. The 2 synergies accounted for 15.9% less variance than that of participants without LBP. Participants with LBP may have used additional muscles not examined in our study to achieve the measured stiffness changes. Individuals with LBP may rely on a global strategy to stabilize the spine and raise the limbs and a different strategy to stabilize the lumbar spine and pelvis.

The lumbar multifidus and erector spinae amplitudes were significantly lower during leg raising in the LBP group, and this may have contributed to the need for a different control strategy during the test. Their ability to obtain spinal stiffening and pain reduction may require larger global synergies. This is supported by a larger portion of the variance being explained by the first synergy. Participants without LBP had a separation of intrinsic stabilizing synergy (the lumbar multifidus and lumbar erector spinae) and global synergy (the thoracic erector spinae and gluteus maximus) patterns, with the intrinsic synergy explaining a larger proportion of variance. Patients with chronic LBP have demonstrated a loss of refined movement control.[40] While participants in this study had acute to subacute pain with low pain and disability ratings, they also demonstrated a reduction in the sophistication of their movement control. Focal motor training has mainly been focused on patients with chronic LBP.[41,42] Further studies in movement coordination of individuals with acute to subacute pain may help to identify whether this type of training would be beneficial in these subgroups.

Limitations

We attempted to maintain parity with clinical performance of the PIT. However, our question required some standardization, such as the magnitude of force during testing. We applied similar forces throughout the test to limit confounding variability and controlled the height of leg raising. While these standardizations did not seem to affect test results, they may affect the generalizability and external validity of our findings, as our procedures may not completely align with test performance in clinical settings.[18] We feel that the testing was performed as close as possible to clinic situations. Participant positioning was matched to clinical parameters, and we added 1 trial with maximal applied force.

We also lacked participants who were unable to reduce or abolish pain with leg raising. Spinal stiffening characteristics and muscle synergy patterns in these individuals could provide further information on the motor strategy of individuals with LBP and clarify the prescriptive value of the test.

Participants with LBP had lower Fear-Avoidance Beliefs Questionnaire, pain, and Oswestry Disability Index scores than what may typically be encountered in the clinic. However, these ratings were comparable to those of participants in the original study identifying the PIT as a predictor for successful intervention.[19] This should be considered in the interpretation of our findings and when administering the test to patients with different LBP characteristics.

CONCLUSION

Spinal stiffness increased and pain was reduced during the PIT in participants with LBP, providing evidence of a muscle-driven spinal stiffness increase during the test. Differences in muscle activation strategies between participants with and without LBP during the PIT suggest a global stabilization in individuals with LBP presenting clinically, similar to our participants, versus an intrinsic muscle stabilization strategy in individuals without LBP. ◉

KEY POINTS

FINDINGS: In contrast to healthy individuals, individuals with low back pain utilize a global stabilizing strategy to stiffen the spine during the prone instability test.

IMPLICATIONS: Patients with acute to subacute low back pain also may demonstrate the reduced sophistication of movement control identified in patients with chronic low back pain.

CAUTION: The standardization of the test in this study may limit generalizability across clinical situations.

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