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Abstract—The current study examined the validity and reliability of a new system that was developed to measure lumbar region passive stiffness and end range of motion during a trunk lateral bending movement in vivo. Variables measured included force, end range lumbar region motion, torque, lumbar region stiffness, and passive elastic energy. Validity of the force measurements was examined using standard weights. Validity of lumbar region angle measurements was examined using an instrumented trunk with an electrogoniometer. Reliability of the measurements between trials within a session was examined in a sample of 50 people (25 men, 25 women; mean +/– standard deviation age = 30.7 +/– 8.9 yr); 31 people reported a history of chronic or recurrent low back pain (LBP) and 19 reported no prior history of LBP. The end range lumbar region motion and force measurements demonstrated an excellent linear relationship with the criterion standard measures. Average error between the criterion standard and observed measurements was minimal for all measurements. For reliability testing, the majority of intraclass correlation coefficient values were >0.75. The validity and reliability of the current system are sufficient to examine lumbar region stiffness and end range of motion in people with and people without LBP.

Key words: low back pain, measurement properties, passive, range of motion, rehabilitation, reliability, spine, stiffness, trunk movement, validity.

INTRODUCTION

Some researchers have suggested that passive stiffness of the lumbar region in vivo may be an important characteristic to examine in people with low back pain (LBP) [1–2]. To date, in vitro studies have focused on passive stiffness of individual muscle fibers and whole muscles [3–5], spinal ligaments [6–7], and individual lumbar motion segments [8–10]. Although these studies provide useful information about the mechanical properties of various individual spinal tissues, the studies do not provide information about how stiffness measures of the individual spinal tissues relate to overall lumbar region stiffness. A measure of overall lumbar region stiffness would include contributions from muscle, tendon, ligament, cartilage, bone, skin, nerve, adipose tissue, and viscera.

Abbreviations: CI = confidence interval, EMG = electromyographic, ICC = intraclass correlation coefficient, LBP = low back pain, MVIC = maximum voluntary isometric contraction, SD = standard deviation.

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The overall stiffness measure is potentially important because it may reflect the stiffness a person encounters during trunk movements in vivo. Information about lumbar region stiffness in vivo may be of importance in a person with LBP because of (1) the potential impact stiffness has on the pattern of movement that the person displays and (2) the suggested relationship between movement patterns and either development or recurrence of an LBP problem [1,11–12]. In particular, characteristics of a trunk lateral bending movement [13–16] have been associated with an increased risk for LBP [17]. Examining lumbar region passive stiffness and end range of motion during a trunk lateral bending motion may provide information about the proposed relationship between the person's movement pattern during trunk lateral bending and LBP.

Many other investigators have examined trunk mobility and stiffness in vivo. Active trunk range of motion, in particular active trunk lateral bending, has been examined in people with and people without LBP [11,18–20]. Investigators have also examined passive stiffness and mobility of individual lumbar spine segments in vivo in healthy individuals [21–22] and differences in posterior-anterior intersegmental stiffness and mobility in people with and people without LBP [23–24]. However, McGill and colleagues were the first to develop a device to examine passive stiffness and end range of motion of the lumbar region during a physiological movement [25]. Briefly, the custom-made device supported the pelvis and lower limbs on a stable platform and the trunk was supported on a low-friction moveable cradle that constrained trunk movement to a single plane [25]. To measure the force required to pull the trunk through a range of movement, a load cell was attached with a cable to the moveable cradle. Lumbar region kinematics were measured with an electromagnetic tracking device. In one study of healthy people, McGill et al. used kinematic and force data to derive measures of passive lumbar region stiffness in each of the three planes of motion (flexion/extension, lateral bending, and axial rotation). They examined differences in stiffness across conditions of belt-wearing, breath-holding, and no support and differences between men and women [25]. Although subject response to the different conditions varied substantially, McGill et al. reported that trunk stiffness increased with belt-wearing compared with the no-support condition during lateral bending and axial rotation but not during flexion [25]. Other researchers also have used McGill et al.'s device to study healthy people. Measures of interest have included (1) time- and activity-dependent changes in lumbar region stiffness [26–27], (2) differences in stiffness between people with different alignments of the spine [28], and (3) differences in stiffness between men and women [29]. The investigators have reported that trunk stiffness (1) does not appear to change with a warm-up activity before exercise [26], (2) decreases during early phases of repetitive lifting but then rebounds toward baseline levels [27], (3) increases after a period of prolonged static positioning in men [26,29], and (4) tends to be greater in people who typically assume a hyperlordotic lumbar spine alignment [28].

Although the prior studies have examined in vivo passive stiffness of the lumbar region during a physiological movement in healthy people, to our knowledge, no studies have examined either (1) lumbar region passive stiffness and end range of motion during a physiological movement in people with LBP or (2) the measurement properties of a device to measure lumbar region passive stiffness and end range of motion during a physiological movement. Our purpose was to examine the validity and within-session reliability of a system that can be used to measure passive stiffness and end range of motion of the lumbar region during trunk lateral bending in vivo. Passive trunk lateral bending was examined because of the proposed relationship between trunk lateral bending movements and LBP [13–17]. The primary use of the system is to measure lumbar region passive stiffness and end range of motion in people with and people without LBP.

METHODS

The system to measure passive stiffness of the lumbar region consists of a passive movement device and a six-camera, three-dimensional motion capture system (Motion Analysis Corporation; Santa Rosa, California). In the current study, lumbar region passive stiffness and end range of motion were examined during a trunk lateral bending movement.

Passive Movement Device

The passive movement device used in the current study is a modification of the device described by McGill and colleagues [25]. The goal of the modifications was to improve the usability and accuracy of the original device.

The new device consists of a table, platform, moveable cradle, two force transducers, and a guide (**Figure 1**). The table is a stable surface that is used to secure the participant's pelvis and lower limbs during passive movement of the trunk. The cradle is a moveable surface that is used to secure the participant's trunk. The cradle glides across the underlying platform on three porous air bearings (NewWay, Inc; Aston, Pennsylvania). Each air bearing is 80 mm in diameter, autoleveling, and capable of supporting a weight of up to 1,112.1 N (250 lb). When continuously supplied with compressed air, the cradle allows for virtually frictionless movement of the trunk in a single plane.

A mounting bracket is attached to the distal end of the moveable cradle and provides a point of attachment for two force transducers (one on each side) and a metal guide. The force transducers (Omegadyne, Inc; Sunbury, Ohio) are stainless steel "S" beam load cells with a ±222.4 N (50 lb) capacity. Attached to each force transducer is a cable that is used to apply force to the transducer. The examiner applies the force in-line with the metal guide to ensure that the line of pull of the cable forms a normal tangent with the distal end of the cradle. When force is applied, the cradle and participant are moved through a trunk lateral bending motion. The signal from the force transducer is amplified and then sampled at 1,200 Hz. The transducer signal is converted through a 12-bit analog-to-digital board and synchronized in time with kinematic data by using the motion capture software. The voltage range for collecting the force data is ±2.5 V, and the resolution for each transducer is 0.13 N.

The force transducers were tested for linearity and hysteresis across the 0–222.4 N (0–50 lb) range. Testing included loading and unloading of the transducers in tension with calibrated weights at 4.4 N (0–89.0 N) and 22.2 N (89.0–222.4 N) increments. The transducers demonstrated acceptable linearity (≥0.99) and a maximal hysteresis of 0.89 N. Before each testing session, each force transducer was also calibrated with seven sequential weights within the 0–222.4 N range so that changes in transducer signal across time during the trunk lateral bending movement could be interpreted as changes in force through data

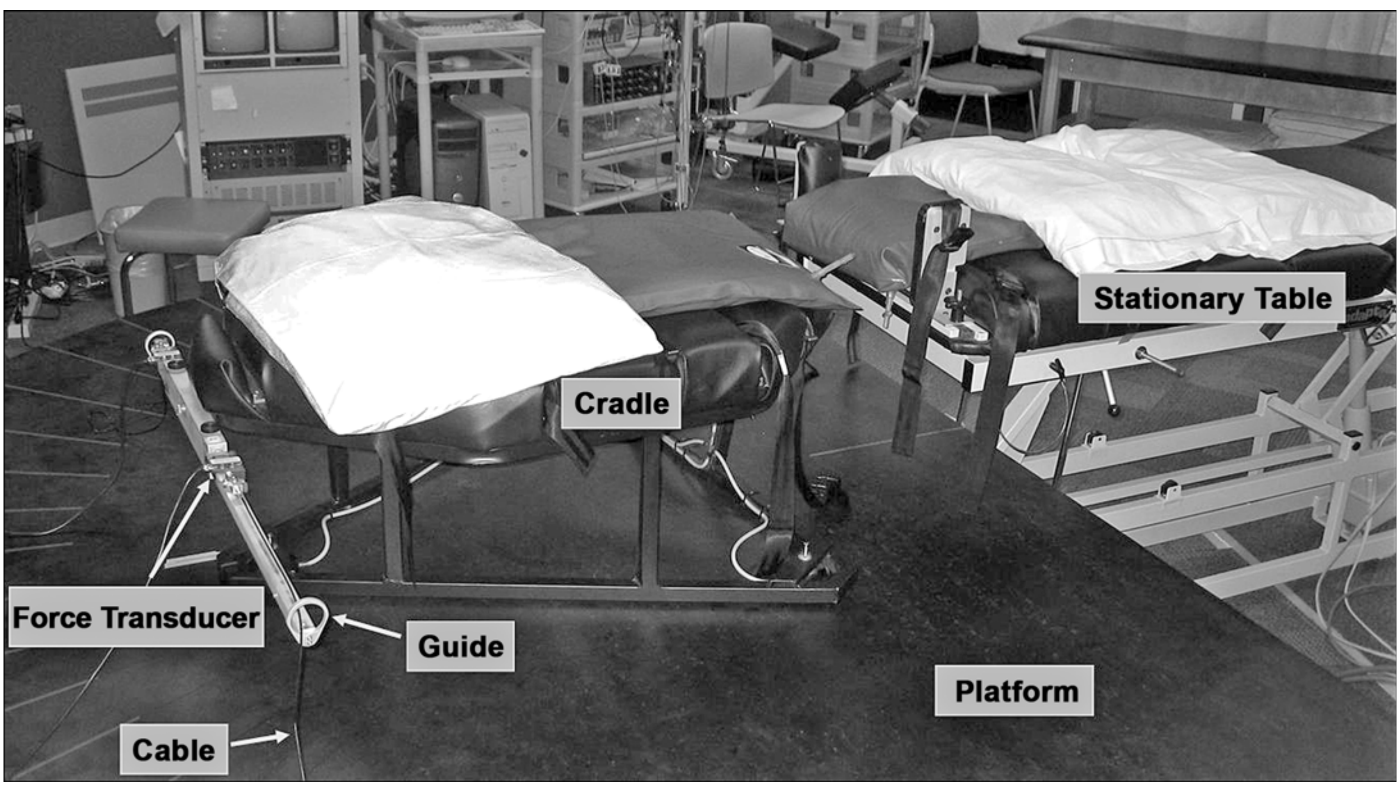

Figure 1.
Passive movement device.

processing. During processing, force data were filtered with a 45 Hz, fourth-order, dual low-pass Butterworth filter.

Motion Capture System

The six-camera motion capture system was used to collect kinematic data during trunk movements. Each camera sampled data at a rate of 60 Hz, and the resolution of the system was 1 mm in any direction for a volume of 1 m^3. Kinematic measurements during trunk lateral bending were based on data from reflective markers placed on specified anatomical landmarks and locations on the device. Marker locations included (1) three markers on the passive movement device along the line of force application, (2) a single marker superficial to the first lumbar vertebra, and (3) a three-marker triad superficial to the second sacral spinous process. The specific marker locations used are depicted in **Figure 2**. Small markers (1.90 cm in diameter) were used for the vertebral and triad markers, and larger markers (2.54 cm in diameter) were used for locations on the passive movement device. During processing, all kinematic data were filtered using a fourth-order, dual low-pass Butterworth filter with a cutoff frequency of 1 Hz. The cutoff frequency was specifically chosen based on the average speed of the passive movements across participants (1.9 ± 0.4 °/s) [30].

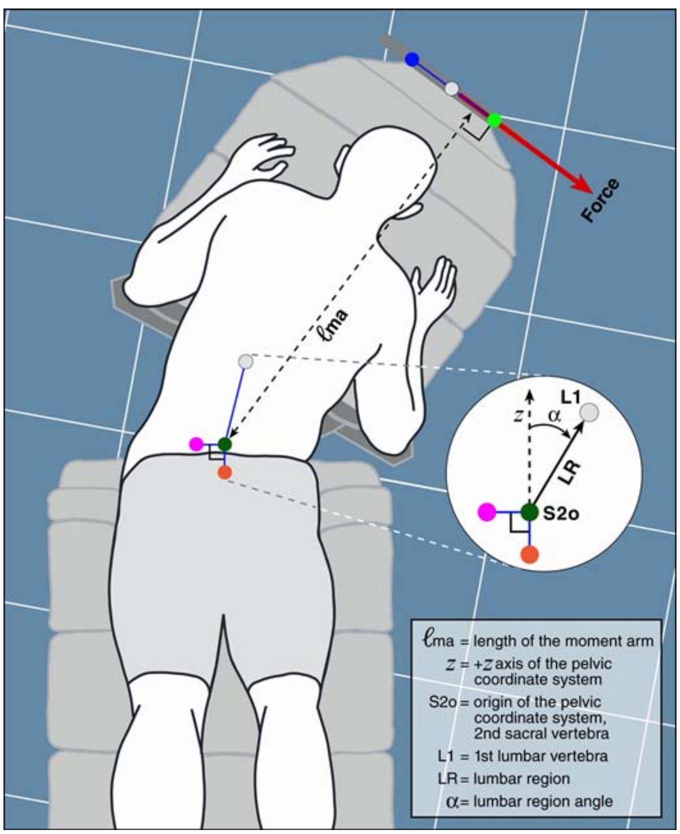

Figure 2.
Marker locations and measurements for deriving stiffness of lumbar region in vivo during trunk lateral bending (frontal plane view).

Measures

Prior studies of passive stiffness of the lumbar region in vivo have included several different kinematic, torque, and stiffness measures [25,27,29]. The following are selected measures that could be useful for examining passive stiffness and end range of motion of the lumbar region in people with and people without LBP. Kinematic measures of interest for deriving measures of lumbar region stiffness and end range of motion during trunk lateral bending include the length of the moment arm and the lumbar region angle. The lumbar region segment was defined by a vector from a reflective marker on the second sacral spinous process (origin marker on the pelvic triad) to a marker on the first lumbar spinous process (**Figure 2**). Lumbar region angle was defined as the relative angle between the lumbar region segment and the superior-inferior (*z*) axis of a local pelvic coordinate system (**Figure 2**). End range of lumbar region motion was calculated as the maximum lumbar region angle during the trunk lateral bending movement. The axis of rotation for the lumbar region was defined by a fixed location of a single marker on the second sacral spinous process. The line of action of the force was defined by two collinear markers on the transducer mounting bracket. The length of the moment arm was defined as the linear distance between the axis of rotation and the line of action of the force (**Figure 2**). The force required to pull an individual passively through a trunk lateral bending movement was measured with a force transducer. For calculation of the torque applied to the lumbar region during trunk lateral bending, the force (in newtons) was multiplied by the moment arm length (in meters). The magnitude of torque at the maximum lumbar region angle was then identified. Stiffness of the lumbar region during trunk lateral bending was defined as the slope of the torque-lumbar region angle curve (torque/lumbar region angle) [25,29]. Torque-angle curves were generated for each trunk lateral bending movement. Torque-angle curves were fit with an exponential function [25] and examined from the start to the maximum of lumbar region motion (**Figure 3**). Lumbar region

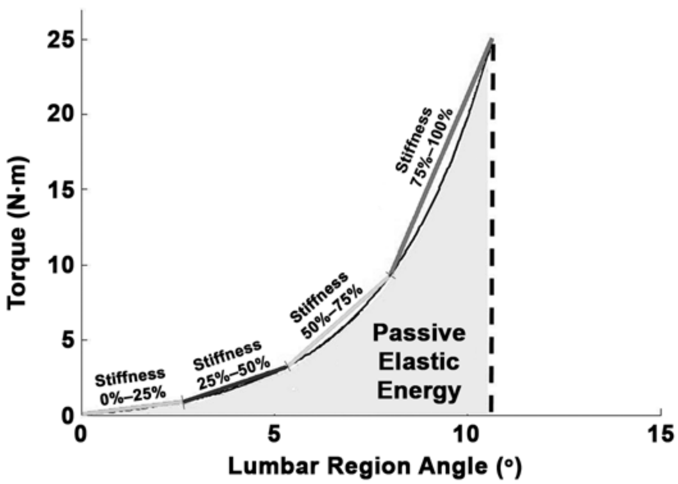

Figure 3.
Representative torque-lumbar region angle curve, with measures of stiffness and passive elastic energy, for one participant during one trunk lateral bending movement.

motion was then segmented into quartiles. The start and end points of the exponential function were determined for each quartile. Lumbar region stiffness was calculated as the linear slope from the start to the end of each quartile of lumbar region motion (0%–25%, 25%–50%, 50%–75%, and 75%–100% of maximum lumbar region motion) (**Figure 3**). Lastly, to derive a measure of passive elastic energy [25], we calculated the area under the torque-lumbar region angle curve from the start to the maximum of lumbar region motion (**Figure 3**).

Validity Testing

To test the validity of the system, we constructed an instrumented trunk (**Figure 4**). The instrumented trunk consisted of two rigid segments, with a precision electrogoniometer (Fred V. Fowler Co Inc; Newton, Massachusetts) at the axis of rotation between the two segments. The precision electrogoniometer has a manufacturer-reported accuracy of 0.017° and is considered the criterion standard for validity testing of lumbar region angle measures. The rigid arms on the instrumented trunk were secured to the tracks on the table and moveable cradle of the passive movement device. The axis of rotation was positioned at the distal edge of the table to approximate the location of a participant's second sacral spinous process. Marker placements on the instrumented trunk and passive movement device were analogous to the marker placements used during passive movement testing (**Figures 2** and **4**). Measurements of moment arm length and lumbar region angle were examined. Moment arm length was considered accurate to ±2 mm on the basis of the error reported by the manufacturer for identifying the position of a reflective marker. To test the validity of the lumbar region angle measure, we moved the instrumented trunk (**Figure 4**) through a trunk lateral bending motion from 0°–35° in 1° increments (gauged by the electrogoniometer).

To examine the validity of the force measures, we attached the transducer mounting bracket to a metal stand to allow vertical orientation of each force transducer separately. First, the load cell was calibrated for a testing session to determine the calibration factor as previously described. Next, the transducer was loaded in tension with precision-calibrated weights ranging from 0–133.4 N (0–30 lb), at 2.2 N (0.5 lb) increments, in a random sequence. The measured load in newtons was calculated based on change in electrical potential from the load cell and the calibration factor.

Reliability Testing

A group of 50 people were tested (25 men, 25 women; mean ± standard deviation (SD) age = 30.7 ± 8.9 years) to examine the reliability of measures of lumbar region passive stiffness and end range of motion with repeated trials during one passive movement testing session. Thirty-one people in the sample reported a history of chronic or recurrent LBP [31] and nineteen reported no history of LBP. Characteristics of the participants in both groups are summarized in **Table 1**. Because pain can potentially affect the ability to relax with passive movements, people with LBP were excluded from participating in the study if their LBP at the time of testing exceeded 3/10 on an 11-point verbal numeric rating scale (0–10, 10 = worst possible pain) [32–33] or if they were in an acute flare-up of the LBP problem on the day of testing [31]. People were also excluded from participating in the study if they reported a history or physician diagnosis of (1) serious spinal complications (e.g., tumor or infection), (2) previous spinal surgery, (3) marked kyphosis or scoliosis, (4) spondylolisthesis, (5) spinal stenosis, (6) spinal instability, (7) spinal fracture, (8) ankylosing spondylitis, (9) degenerative disc disease, (10) disc herniation, (11) lower-limb impairment such as previous lower-limb surgery or leg-length discrepancy, (12) severe

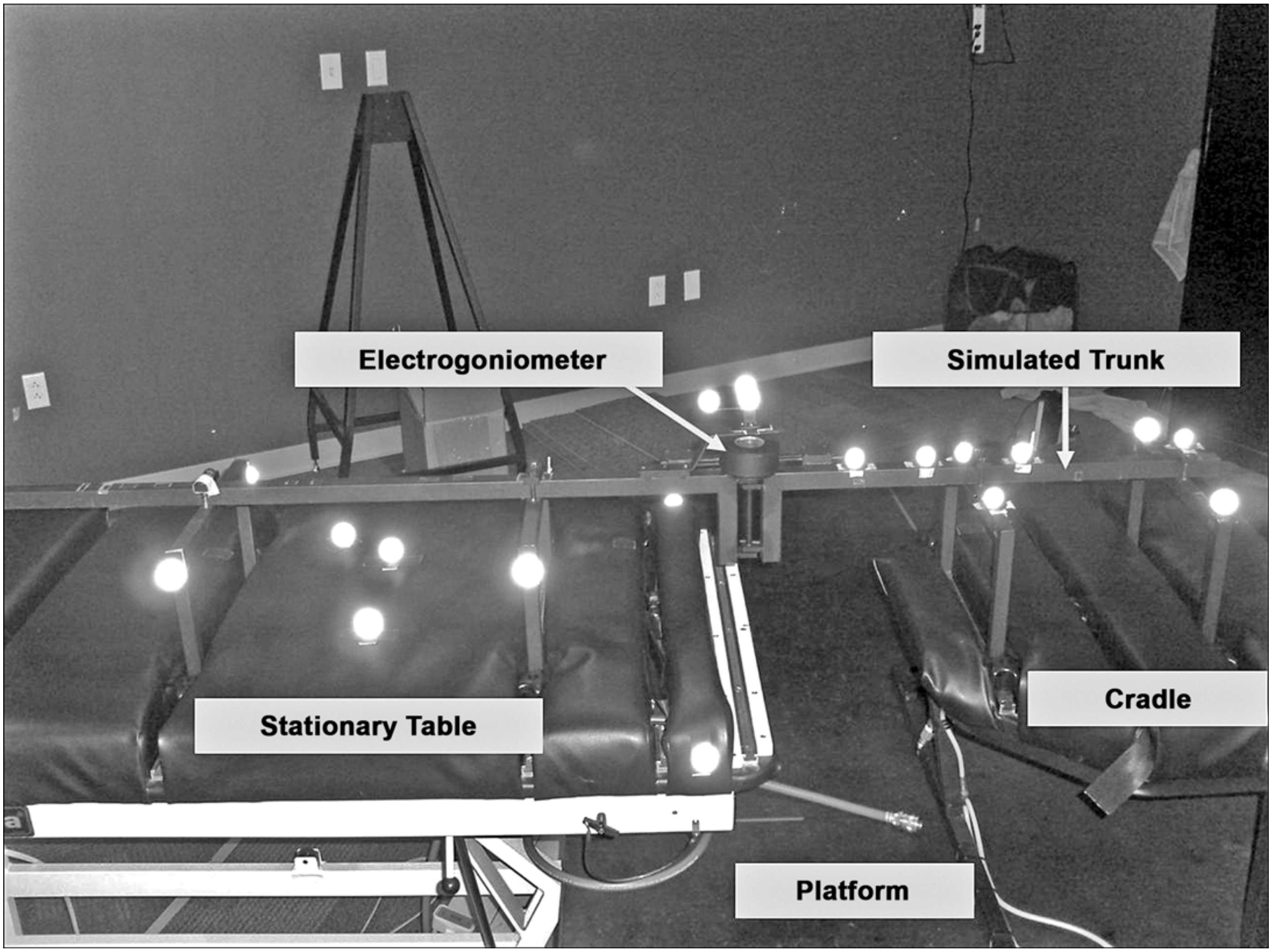

Figure 4.
Instrumented trunk with precision electrogoniometer (side view).

Table 1.
Differences in characteristics of people with and people without low back pain (LBP).

Characteristic	With LBP (*n* = 31)	Without LBP (*n* = 19)	Statistic	*df*	*p*-Value
Age (yr) (mean ± SD)	31.0 ± 9.3	30.3 ± 8.5	$t = 0.26$	48	0.80
Sex (*n*)					
Female	16	9	$\chi^2 = 0.09$	1	0.77
Male	15	10			
Weight (kg) (mean ± SD)	71.3 ± 13.1	70.2 ± 15.1	$t = 0.27$	48	0.79
Height (cm) (mean ± SD)	171.2 ± 9.3	169.2 ± 9.6	$t = 0.74$	48	0.46
Body Mass Index ($kg \cdot m/s^2$) (mean ± SD)	24.2 ± 2.9	24.2 ± 3.0	$t = -0.06$	48	0.95
Baecke Score (3–15) (mean ± SD)	8.2 ± 2.3	8.9 ± 1.0	$t = -1.26$	48	0.21

df = degrees of freedom, SD = standard deviation.

neurological involvement, (13) rheumatoid arthritis, (14) neurological disease that required hospitalization, (15) history of unresolved cancer, (16) osteoporosis, or (17) current pregnancy. The testing protocol was approved by the Human Studies Committee at Washington University School of Medicine, and all participants read and signed an informed consent document describing the protocol. The rights of subjects were protected throughout the testing process.

Participants completed self-report measures that included (1) a demographic and LBP history questionnaire [34], (2) a verbal numeric rating scale of symptoms (LBP group only) [32–33], (3) the Modified Oswestry Disability Index (LBP group only) [35], and (4) the Baecke Habitual Activity questionnaire [36]. The data from the self-report measures for both groups are summarized in **Table 1** and the LBP history and symptom characteristics for participants with LBP in **Table 2**.

Passive Movement Testing

First, the examiner palpated anatomical landmarks and marked the location for reflective markers (**Figure 2**). Next, electromyographic (EMG) electrodes were applied and maximum voluntary isometric contraction (MVIC) testing was performed. The EMG data were collected using a Myosystem 1400A (Noraxon USA, Inc; Scottsdale, Arizona) to monitor activity of agonist and antagonist muscles during passive movements. Bipolar surface electrodes with an interelectrode separation of 2 cm were used to record muscle activity. Electrodes were placed on the external oblique and lumbar erector spinae muscles bilaterally. Electrodes for the external oblique muscles were placed on the lateral most portion of the muscle just inferior to the ribs and were oriented in an inferior-medial direction, parallel with the line of action of the muscle. For the MVIC test for the external oblique muscles, the participant performed an isometric trunk curl-up while the examiner provided resistance. The isometric trunk curl-up was performed with rotation to the left for the right external oblique muscle and rotation to the right for the left external oblique muscle. Electrodes for the lumbar erector spinae muscles were placed 3 cm lateral to the third lumbar spinous process and were oriented in a superior-inferior direction [37]. For the MVIC test for the lumbar erector spinae muscles, the participant performed isometric trunk extension in a prone position while the examiner provided resistance. All electrode placements were confirmed with palpation during MVIC testing. The EMG data were sampled at a rate of 1,200 Hz and bandpass filtered during data collection at 10 to 500 Hz. The EMG data were converted with a 12-bit analog-to-digital board and synchronized in time with kinematic data by using the motion capture software. Lastly, the EMG data were full-wave rectified, filtered with a 45 Hz, fourth-order, dual low-pass Butterworth filter using custom software.

Table 2.
Characteristics of people with low back pain (LBP) (n = 31).

Characteristic	Mean ± SD or *n*	Range
Symptom Intensity (0–10)*		
Before movement testing	2.0 ± 1.2	0.0–3.8
After movement testing	1.3 ± 1.0	0.0–3.5
Average past 7 d	2.3 ± 1.2	0.0–5.5
People with Increased Symptoms During Passive Trunk Lateral Bending†		
Left trunk lateral bending	8	—
Right trunk lateral bending	3	—
Both right and left	9	—
Neither right nor left	11	—
Duration of LBP (yr)	7.0 ± 5.0	0.5–20.0
No. of Episodes of LBP Past 12 mo	3.6 ± 3.0	0.0–12.0
Modified Oswestry Disability Index Score (0%–100%)	14.1 ± 0.8	2.0–40.0

*Pain intensity was measured on 0–10 numeric rating scale.
†Symptoms were increased during one or more of the three trials of passive trunk lateral bending in the specified direction.
SD = standard deviation.

Each participant was then positioned lying prone on the passive movement device with the pelvis and lower limbs on the table, the iliac crests in line with the end of the table, and the pelvis in neutral rotation. The fourth lumbar vertebra was centered between the table and moveable cradle, and the trunk was supported on the cradle to the level of the third lumbar vertebra. The participant was secured to both the table and cradle with versaform pillows, padded clamps, and straps. The examiner palpated anatomical landmarks on the spine and limbs and placed the reflective markers on the participant and the device (**Figures 1** and **2**).

Each movement trial was started with the participant's lumbar region in a neutral position. Neutral position was defined as the position at which the reflective markers on the first and fourth lumbar and second sacral spinal processes were collinear as approximated with a yardstick. This neutral position was then confirmed by collecting data with the participant in the neutral position and calculating the lumbar region angle with a custom software program. If the lumbar region angle was not within 1° of zero, then the neutral position was corrected. The position of the moveable cradle relative to the platform was marked in the identified neutral position. The marked position served as the starting position of the cradle for each trial.

Following application of markers, each participant was secured in the passive movement device and trials of passive trunk lateral bending were performed. For each trial, the participant was instructed to relax completely while the examiner moved him or her passively through a maximum trunk lateral bending motion. The trial was concluded when the participant verbally reported that he or she was at a tolerable limit or when the examiner was unable to apply additional force [25]. Change in LBP symptom behavior during the trunk lateral bending motion relative to the neutral position was also assessed using the verbal numeric rating scale. The percentage of people reporting increased symptoms during passive trunk lateral bending is summarized in **Table 2**. Three repetitions of passive movements were performed to each side. The side (right or left) to which a subject was moved for the first trial was randomized. Speed of movement was controlled by moving the cradle a fixed distance for each beat of a metronome (at 72 bpm). The examiner moved the participant for at least three practice passive trials before beginning testing in a new movement direction. The practice trials were performed to account for viscoelastic creep in tissues of the lumbar region [38] and to ensure a stable stiffness measure. Muscle activity during passive movement testing was monitored and expressed as a percentage of the individual's MVIC. A movement was considered passive if the activity of muscles opposing the movement direction did not exceed 2 percent of the participant's MVIC for a period of 0.3 s during the trial [28].

Analysis

Validity Testing

In the biomechanics literature, stiffness is often defined as the slope of the torque-angle curve [25,29,39]. The validity of this derived stiffness measure, however, cannot be directly tested against a criterion standard. To examine the validity of the lumbar region stiffness measure, therefore, we tested the validity of components of the stiffness measure (force, lumbar region angle). The relationship between the variables of interest, force and lumbar region angle, and their criterion standards was examined. Average error for each measure then was calculated and the error of the lumbar region stiffness measure was derived as a composite of the average errors from each component measure.

To examine the relationship between the electrogoniometer value and the calculated lumbar region angle across the 35° range, we conducted a linear regression analysis, regressing calculated lumbar region angle values on electrogoniometer values. To index error of the measure, we also examined the average difference between the electrogoniometer value and the calculated lumbar region angle. To examine the relationship between the applied load (calibrated weight) and the measured load, we conducted a linear regression analysis, regressing measured load values on applied load values. To index error of the measure, we also examined the average difference between the applied load and measured load.

Stiffness is a composite measure of force, moment arm length, and lumbar region angle. To calculate the error of a measure that is the product or quotient of two or more measures, the percentage error of the composite measure is found by summing the percentage errors of the component measures [40]. Absolute error can then be calculated by multiplying the percentage error of the composite measure by the range of tested values [40]. For the current study, error of the stiffness measure was calculated based on the (1) mean difference between the applied load and measured load (F_{error}), (2) mean difference between the electrogoniometer value and calculated lumbar region angle (LR_{error}), (3) reported error for the moment arm length (MA_{error}), and (4) range of values or average values for measures of force, moment arm length, torque, lumbar region angle, and lumbar region stiffness (F_{range}, MA_{avg}, T_{range}, LR_{range}, $LRStiff_{avg}$, respectively). In the case of the torque measure (force × moment arm), error was calculated using **Equation (1)**:

$$T_{error} = (F_{range}) \times (MA_{avg}) \times [1 \pm ((F_{error} \div F_{range}) + (MA_{error} \div MA_{avg}))] . \quad \mathbf{(1)}$$

Error for the lumbar region stiffness measure then was calculated in the same way by using the derived error for the torque measure (T_{error}) from **Equation (1)** and the following equation (**Equation (2)**):

$$LRStiff_{error} = (LRStiff_{avg}) \times [1 \pm ((T_{error} \div T_{range}) + (LR_{error} \div LR_{range}))] . \quad \mathbf{(2)}$$

Reliability Testing

The intraclass correlation coefficient (ICC) (3,1) [41], 95% confidence interval (CI) for the ICC value, and the standard error of the measure [42] were calculated to index reliability of repeated measures within a single session for each direction (right, left) of the trunk lateral bending movement for each of the following measures: (1) end range lumbar region motion (maximum lumbar region angle), (2) torque at maximum lumbar region angle, (3) lumbar region stiffness within each quartile (0%–25%, 25%–50%, 50%–75%, and 75%–100% maximum lumbar region motion), and (4) passive elastic energy (area under the torque-angle curve for the lumbar region).

RESULTS

For testing the validity of the measure of lumbar region end range of motion, the unstandardized regression coefficient (*B*) from the linear regression of calculated lumbar region angle on electrogoniometer value was 1.006 (95% CI: 0.993–1.019). The mean ± SD difference between the electrogoniometer value and calculated lumbar region angle (lumbar-region error) was 0.35° ± 0.46°. For testing the validity of the force measure, the unstandardized regression coefficient (*B*) from a linear regression of measured load values on applied load values (calibrated weight) was 1.003 (95% CI: 1.001–1.005) and 1.000 (95% CI: 1.000–1.000) for the two force transducers, respectively. The mean ± SD difference between the applied and calculated loads (F_{error}) for both transducers was 0.40 ± 0.27 N. Reported error for the moment arm length (MA_{error}) is 0.002 m (Motion Analysis Corporation). The average error for the torque measure (T_{error}) was 0.72 N·m. Average error for the lumbar region stiffness measure ($LRStiff_{error}$) was 0.14 N·m/°. Percent error of the lumbar region stiffness measure was 1.5 percent.

Mean ± SD values for each trial for all kinematic, torque, and stiffness measures are reported for people with LBP in **Table 3** and for people without LBP in **Table 4**. Reliability indices, including the ICC (3,1) and standard error of the measure [42] are reported for all kinematic, torque, and stiffness measures for people with LBP in **Table 5** and for people without LBP in **Table 6**. Confidence intervals for the ICC values are also reported. For people with LBP, values for the ICC ranged from 0.60 to 0.91, with the majority of ICC values >0.75. For people without LBP, values for the ICC ranged from 0.38 to 0.87, with the majority of ICC values >0.65.

DISCUSSION

Results from the current study indicate that the validity of the lumbar region angle measure and force measure is excellent when compared with criterion standard measures. Average error with the described system to measure stiffness of the lumbar region is 0.14 N·m/°, and the average error associated with measuring end range of lumbar region motion is 0.35° ± 0.46°. Results from reliability testing also provide us with information about the repeatability of measures of stiffness and end range of motion within a test session in people with and people without LBP. The ICC values for the majority of measures for both groups were >0.75. Measures of stiffness and end range of motion must be valid and reliable to be useful for studying the relationship between the measures and LBP.

Specifically, the system for measuring passive stiffness and end range of motion of the lumbar region in vivo could be used to examine a number of different questions. For example, the system could be used to examine differences in these two variables between people with and people without LBP. Lumbar region passive stiffness and end range of motion during a physiological movement are factors that

Table 3.
Mean ± standard deviation values for kinematic, torque, and stiffness measures for each trial for people with chronic or recurrent low back pain (n = 31).

Measure	Trial 1	Trial 2	Trial 3	*F*-Statistic	*df*	*p*-Value
Maximum Lumbar Region Angle (°)						
Left	11.59 ± 3.18	12.02 ± 3.36	11.76 ± 3.04	0.16	2	0.85
Right	12.00 ± 3.07	11.64 ± 3.28	12.02 ± 3.23	1.11	2	0.34
Torque (N·m)						
At left maximum lumbar region angle	30.66 ± 13.19	28.95 ± 13.19	29.68 ± 12.59	0.54	2	0.59
At right maximum lumbar region angle	29.32 ± 11.46	29.17 ± 10.99	30.84 ± 12.84	0.08	2	0.93
Stiffness (N·m/°)						
0%–25% left lumbar region angle	0.36 ± 0.31	0.38 ± 0.35	0.34 ± 0.30	0.24	2	0.79
0%–25% right lumbar region angle	0.42 ± 0.37	0.37 ± 0.25	0.42 ± 0.34	0.76	2	0.47
25%–50% left lumbar region angle	0.89 ± 0.61	0.88 ± 0.69	0.84 ± 0.58	0.35	2	0.71
25%–50% right lumbar region angle	0.98 ± 0.71	0.88 ± 0.52	0.97 ± 0.71	0.58	2	0.56
50%–75% left lumbar region angle	2.30 ± 1.33	2.14 ± 1.36	2.16 ± 1.10	0.69	2	0.51
50%–75% right lumbar region angle	2.31 ± 1.40	2.21 ± 1.18	2.36 ± 1.61	0.10	2	0.91
75%–100% left lumbar region angle	6.54 ± 4.00	5.74 ± 2.91	6.10 ± 2.77	0.36	2	0.70
75%–100% right lumbar region angle	5.75 ± 3.06	6.01 ± 3.19	6.27 ± 4.04	0.16	2	0.85
Passive Elastic Energy (N·m·°)						
Area under left torque-lumbar region angle curve	111.30 ± 60.59	109.64 ± 62.57	106.42 ± 57.18	1.04	2	0.36
Area under right torque-lumbar region angle curve	111.94 ± 55.60	108.84 ± 55.40	112.97 ± 50.36	0.11	2	0.90

df = degrees of freedom.

Table 4.
Mean ± standard deviation values for kinematic, torque, and stiffness measures for each trial for people without low back pain (n = 19).

Measure	Trial 1	Trial 2	Trial 3	*F*-Statistic	*df*	*p*-Value
Maximum Lumbar Region Angle (°)						
Left	12.30 ± 3.28	12.32 ± 3.36	11.92 ± 3.29	0.30	2	0.74
Right	13.23 ± 3.47	12.16 ± 3.42	12.57 ± 3.45	3.37	2	0.05
Torque (N·m)						
At left maximum lumbar region angle	26.18 ± 9.85	26.22 ± 12.20	24.02 ± 9.78	2.18	2	0.13
At right maximum lumbar region angle	28.84 ± 13.29	28.85 ± 13.49	27.25 ± 11.84	0.75	2	0.48
Stiffness (N·m/°)						
0%–25% left lumbar region angle	0.23 ± 0.17	0.25 ± 0.16	0.26 ± 0.17	1.08	2	0.35
0%–25% right lumbar region angle	0.26 ± 0.19	0.29 ± 0.21	0.31 ± 0.18	0.36	2	0.70
25%–50% left lumbar region angle	0.61 ± 0.29	0.63 ± 0.28	0.64 ± 0.31	0.62	2	0.55
25%–50% right lumbar region angle	0.64 ± 0.36	0.76 ± 0.49	0.75 ± 0.39	0.75	2	0.48
50%–75% left lumbar region angle	1.71 ± 0.61	1.74 ± 0.78	1.63 ± 0.62	0.17	2	0.84
50%–75% right lumbar region angle	1.74 ± 0.78	2.03 ± 1.24	1.91 ± 0.95	1.45	2	0.25
75%–100% left lumbar region angle	5.19 ± 2.49	5.25 ± 3.38	4.79 ± 2.75	1.36	2	0.27
75%–100% right lumbar region angle	5.14 ± 2.91	5.78 ± 3.54	5.07 ± 2.72	2.16	2	0.13
Passive Elastic Energy (N·m·°)						
Area under left torque-lumbar region angle curve	99.69 ± 42.00	97.65 ± 39.45	95.50 ± 49.52	0.48	2	0.63
Area under right torque-lumbar region angle curve	119.12 ± 51.71	109.04 ± 48.98	110.45 ± 49.96	1.34	2	0.28

df = degrees of freedom.

Table 5.

Intraclass correlation coefficient (ICC), 95% confidence interval (CI) for ICC, and standard error of measure (SEM) values for kinematic, torque, and stiffness measures for people with chronic or recurrent low back pain ($n = 31$).

Measure	ICC (3,1)*	95% CI for ICC	SEM†
Lumbar Region Angle (°)			
Left	0.89	0.81–0.94	1.03
Right	0.91	0.84–0.95	1.01
Torque (N·m)			
At left maximum lumbar region angle	0.79	0.65–0.89	6.23
At right maximum lumbar region angle	0.77	0.62–0.88	5.85
Stiffness (N·m/°)			
0%–25% left lumbar region angle	0.81	0.67–0.89	0.14
0%–25% right lumbar region angle	0.70	0.53–0.84	0.17
25%–50% left lumbar region angle	0.86	0.75–0.92	0.24
25%–50% right lumbar region angle	0.79	0.66–0.89	0.29
50%–75% left lumbar region angle	0.83	0.71–0.91	0.53
50%–75% right lumbar region angle	0.79	0.65–0.89	0.65
75%–100% left lumbar region angle	0.60	0.40–0.77	2.06
75%–100% right lumbar region angle	0.64	0.45–0.80	2.10
Passive Elastic Energy (N·m·°)			
Area under left torque-lumbar region angle curve	0.91	0.85–0.96	17.91
Area under right torque-lumbar region angle curve	0.80	0.67–0.89	24.64

*Hopkins WG. Measures of reliability in sports medicine and science. Sports Med. 2000;30(1):1–15. [PMID: 10907753]

†Batterham AM, George KP. Reliability in evidence-based clinical practice: A primer for allied health professionals. Phys Ther Sport. 2003;4(3):122–28.

Table 6.

Intraclass correlation coefficient (ICC), 95% confidence interval (CI) for ICC, and standard error of measure (SEM) values for kinematic, torque, and stiffness measures for people without low back pain ($n = 19$).

Measure	ICC (3,1)*	95% CI for ICC	SEM†
Lumbar Region Angle (°)			
Left	0.87	0.73–0.95	1.19
Right	0.86	0.72–0.94	1.30
Torque (N·m)			
At left maximum lumbar region angle	0.84	0.66–0.94	4.09
At right maximum lumbar region angle	0.88	0.75–0.95	4.53
Stiffness (N·m/°)			
0%–25% left lumbar region angle	0.45	0.13–0.74	0.13
0%–25% right lumbar region angle	0.38	0.08–0.67	0.15
25%–50% left lumbar region angle	0.58	0.28–0.82	0.19
25%–50% right lumbar region angle	0.52	0.23–0.77	0.30
50%–75% left lumbar region angle	0.73	0.48–0.89	0.36
50%–75% right lumbar region angle	0.75	0.53–0.89	0.52
75%–100% left lumbar region angle	0.68	0.41–0.86	1.41
75%–100% right lumbar region angle	0.86	0.72–0.94	1.16
Passive Elastic Energy (N·m·°)			
Area under left torque-lumbar region angle curve	0.81	0.61–0.92	19.48
Area under right torque-lumbar region angle curve	0.79	0.60–0.91	22.61

*Hopkins WG. Measures of reliability in sports medicine and science. Sports Med. 2000;30(1):1–15. [PMID: 10907753]

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may be related to the movement pattern a person with LBP displays and, potentially, to mechanisms underlying the LBP problem. Other investigators have examined posterior-anterior intersegmental mobility and stiffness of the lumbar region in people with and people without LBP [23–24]. On the basis of these studies, people with LBP appear to demonstrate greater posterior-anterior mobility [23] and stiffness [43] during episodes of LBP. However, to our knowledge, no investigators have examined lumbar region passive stiffness and end range of motion during a physiological movement in people with and people without LBP. Understanding the group differences in stiffness and end range of motion may help us (1) understand the contribution of these two variables to LBP problems, (2) select appropriate intervention for people with LBP that addresses the contributing factors, and (3) provide information about prognosis when using specific interventions directed at the contributing factors.

The system could also be used to examine differences in lumbar region stiffness and end range of motion between subgroups of people with LBP. Prior data suggest that subgroups of people with LBP problems display different patterns of movement during clinical tests of trunk and limb movements [11–12]. Stiffness and end range of motion are two factors that could contribute to the identified subgroup differences. In the current study, stiffness was measured as the linear slope of the torque-lumbar region angle curve at 25 percent increments of lumbar region motion. Measures of stiffness in different increments of lumbar region motion provide us with information about the passive resistance to movement of the lumbar region, a potential factor contributing to identified subgroup differences in movement patterns of the lumbar region during a trunk lateral bending movement [11]. Differences in stiffness or end range of motion between subgroups may indicate differences in the factors contributing to the LBP problems. A difference between subgroups in contributing factors would suggest that different intervention strategies may be required to address the factors. In order to apply the results of such studies to specific intervention strategies, future studies could focus on examining the relationship between the instrumented measures of passive tissue characteristics described in the current study and clinical assessments of stiffness. Future studies could also examine how intervention for an LBP problem affects passive stiffness and end range of motion of the lumbar region. However, to examine such time-dependent changes in passive tissue characteristics, additional examination of the test-retest reliability of the system would be required to determine the minimal detectable change in the measures.

For people without LBP, ICC values were <0.60 for measures of passive stiffness during the first 50 percent of lumbar region motion. We examined the mean values between movement trials and the range of values across trials for each stiffness measure. There were no significant differences between movement trials for measures of passive stiffness ($p > 0.35$), but the range of stiffness values was substantially smaller for the group of people without LBP. Restriction in the range of values for a measure can result in attenuation of the correlation, despite consistency of the measure [43]. For people without LBP, stiffness measures with lower ICC values also appear to have standard errors that are similar to the standard errors in the LBP group. A lack of significant differences between trials for people without LBP and similar standard errors between groups suggests that the stiffness measures are reliable. The ICC values for the group of people without LBP appear to be attenuated as a result of a restriction in the range of measured values.

Values obtained from the current study can be compared with findings from McGill et al.'s study examining lumbar region passive stiffness in healthy individuals. However, the comparisons are limited because of the varying methods for reporting data [25]. McGill et al. reported that end range lumbar region motion in healthy individuals ranged up to 20°. In the current study, end range lumbar region motion ranged up to 22.1° for people without LBP and up to 18.7° for people with LBP. McGill et al. reported values for lumbar region stiffness ranging from 0.32–2.16 N·m/° across the range of motion, while values for lumbar region stiffness in the current report ranged from 0.28–5.40 N·m/° for people without LBP and from 0.39–6.10 N·m/° for people with LBP. The differences in magnitude of stiffness between McGill et al.'s study and the current study may be attributed to a difference in the defined end point for analysis of the torque-angle curve with each study. The end point used in McGill et al.'s analysis of stiffness was the maximum torque that all participants could tolerate. Limiting the analysis in this way did not allow for capturing stiffness values in the later phases of the trunk lateral bending motion in people who displayed larger torque values during these phases. Differences in measures between the current study and the McGill et al. study also could be related to subject position. In McGill et al.'s study, subjects were positioned supine on the device. In the current study, subjects were positioned prone to allow visualization of the reflective markers with the motion capture system.

One limitation of the current study is that people with LBP were required to meet specific inclusion criteria to participate. These criteria may diminish the generalizability of the results to people who present with other conditions or are in an acute flare-up of an LBP problem. A second limitation of the current study is that validity of the derived stiffness measure could not be tested directly. Because stiffness is a composite measure of force, moment arm length, and angle, no method exists for directly testing the validity of the slope of the torque-lumbar region angle curve against a criterion standard. To address this issue, we tested the validity of components of the stiffness measure against their criterion standards and calculated error for the stiffness measure as a weighted sum of the errors for each component measure. A third limitation is that, rather than calculating an instantaneous axis of rotation, we defined the axis of rotation for the lumbar region as a fixed point at the marker superficial to the second sacral spinous process. However, inspection of the data showed that lateral bending of the lumbar region appeared to occur about the axis at the marker on the second sacral spinous process in the majority of cases. Also, due to the relative length of the moment arms (115 ± 3 cm), small variations in the location of the instantaneous axis of rotation would likely result in very little change in the derived torque measure. A fourth limitation is that although three warm-up trials were performed to account for viscoelastic creep in the tissues of the lumbar region, additional creep could potentially have occurred during the three test trials. However, the average values for peak torque appear stable (**Tables 3** and **4**), which suggests that no appreciable creep occurred across the three test trials. The current study also only examined the measurement properties of lumbar region passive tissue characteristics during a physiological movement in the frontal plane. Future studies could examine measures during physiological movements in other planes of motion. Finally, in the current study, intratester reliability was examined between trials within a single testing session. Future studies may require testing different aspects of the reliability of the instrumentation. In order to examine time-dependent changes in passive tissue characteristics, examine changes in passive tissue characteristics with intervention, or allow multiple examiners to use the instrumentation, it may be useful to have test-retest and intertester reliability of the measures.

CONCLUSIONS

Measures of force and lumbar region angle are valid when compared with criterion standards, and percent error of the stiffness measure was minimal when we used a system to measure participants' passive stiffness and end range of motion of the lumbar region during trunk lateral bending in vivo. The system also demonstrated acceptable reliability for measuring lumbar region stiffness and end range of motion during trunk lateral bending. Validity and reliability of the system are sufficient to examine stiffness and end range of motion of the lumbar region in people with and people without LBP.

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