Correlations Between Individuals' Characteristics and Spinal Stiffness in Individuals With and Without Back Pain: A Combined Analysis of Multiple Data Sets

Isabelle Pagé, DC, PhD,[a] Michael Swain, MChiroprac, MPhil,[b] Arnold Wong, PhD,[c] Alexander Breen, PhD,[d] Diana De Carvalho, DC, PhD,[e] Martin Descarreaux, DC, PhD,[f] Martha Funabashi, PhD,[g] and Gregory Kawchuk, DC, PhD[h]

Abstract

Objective: The purpose of this study was to describe the correlations between individual characteristics and spinal stiffness as measured with different spinal stiffness measurement devices in individuals with and without back pain.
Methods: A secondary analysis of 3 adult data sets obtained using 3 different devices, in 2 spinal regions, from a total of 5 separate cross-sectional studies was conducted. Differences in spinal stiffness between men and women and in the strength of correlations among spinal stiffness and age and anthropometric characteristics were evaluated using either the *t* test for independent samples, Pearson's correlation coefficient, or Kendall's τ rank correlation coefficient.
Results: As expected, results varied between data sets; however, few factors had consistent correlations. Specifically, spinal stiffness was significantly lower in women than men in all 3 data sets. Height was positively correlated with spinal stiffness across all data sets. Although weight was correlated with thoracic stiffness, its correlation with lumbar stiffness varied. In 2 data sets, body mass index was inversely associated with lumbar spinal stiffness, whereas results from the thoracic spine region revealed a positive correlation. The results for 1 data set suggest that physiological measurement evaluating body weight distribution may also affect spinal stiffness; however, the specific correlation remains unclear.
Conclusion: Despite data set differences, significant correlations were observed, indicating that participants' characteristics appear to affect spinal stiffness measurement. (J Manipulative Physiol Ther 2018;41:734-752)
Key Indexing Terms: *Back Pain; Association; Spine; Complementary Therapies*

[a] Department of Anatomy, Université du Québec à Trois-Rivières, Trois-Rivières, Québec, Canada.
[b] Department of Chiropractic, Faculty of Science and Engineering, Macquarie University, Sydney, Australia.
[c] Department of Rehabilitation Sciences, Faculty of Health and Social Sciences, The Hong Kong Polytechnic University, Hong Kong.
[d] Center for Biomechanics Research, AECC University College, Bournemouth, United Kingdom.
[e] Discipline of Medicine, Faculty of Medicine, Memorial University of Newfoundland, St. John's, Newfoundland, Canada.
[f] Department of Human Kinetics, Université du Québec à Trois-Rivières, Trois-Rivières, Québec, Canada.
[g] Division of Research, Canadian Memorial Chiropractic College, Toronto, Ontario, Canada.
[h] Department of Physical Therapy, Faculty of Rehabilitation Medicine, University of Alberta, Edmonton, Alberta, Canada.
Corresponding author: Isabelle Pagé, DC, PhD, Department of Anatomy, Université du Québec à Trois-Rivières, 3351 Boulevard des Forges, C.P. 500, Trois-Rivières, QC G8Z 4M3, Canada. (e-mail: *Isabelle.page1@uqtr.ca*).
Paper submitted February 20, 2018; in revised form April 16, 2018; accepted April 23, 2018.
0161-4754

https://doi.org/10.1016/j.jmpt.2018.04.006

Introduction

Low back pain (LBP) and neck pain have been the number one cause of disability globally since 1990.[1] Although the causes of spinal pain are largely unknown, it is believed that most are mechanical in nature.[2,3] As such, clinicians typically use physical assessments to categorize patients with different biomechanical dysfunctions to inform their clinical decision process.[4]

Spinal stiffness is one of the most commonly investigated biomechanical properties of the spine used in the prognosis or treatment decision-making pathways of manual therapy practitioners. It is thought that spinal stiffness may be related to pain or be altered by treatments.[5] To assess the spinal stiffness of a patient, a clinician usually applies manual posteroanterior force to a spinal region (eg, thoracic region) or to individual spinal landmarks along the spine (eg, spinal processes) and subjectively judges the corresponding spinal movement or stiffness. On the basis of the clinician's experience, spinal movement can be perceived as normal, hypermobile, or hypomobile, which is used to guide treatment. Although manual spinal stiffness assessments have traditionally been included in the clinical evaluation of spinal biomechanics, the reliability of these manual assessments has been found to be limited.[5] Accordingly, various spinal stiffness testing devices have been developed to quantify the procedure and have been reported to improve accuracy and reliability.[6] As a result of these improvements, a number of studies have now been conducted with these devices and demonstrate the responsiveness of spinal stiffness to various interventions or treatment.[7,8]

Although the design of spinal stiffness devices varies, the basic principles of instrumented spinal stiffness measurement are similar. A typical spinal stiffness device comprises a motor to control the movement of an indenter that loads the spine of a prone participant, a load cell to measure the loading force, and a displacement sensor to measure the displacement of the indenter (indirect displacement of the spine) in response to the indentation.[6] Importantly, the device is anchored to a stable reference point and is not a handheld device. With the collected force and displacement data, 2 spinal stiffness coefficients (global and terminal) can be calculated from the force-displacement (*F-D*) curve (Fig 1). For both coefficients, an increase in magnitude implies an increase in spine stiffness.

Although the overarching goal of any spinal stiffness testing device is to objectively measure spinal stiffness, characteristics of the individual being assessed, such as sex, age, weight, height, body mass index (BMI), and back pain symptoms, may affect the measurement results.[9-13] However, the relation between these variables and spinal stiffness as measured by different devices remains unknown.[9,11,14-18] Given that different clinicians or researchers may use different devices for clinical assessment or research, it is paramount to understand the impact of different devices, and of testing protocols, in moderating the relations between individuals' characteristics and spinal stiffness. The findings can ultimately help interpret and compare spinal stiffness values between studies and clinical conditions. Unfortunately, no studies have been conducted to evaluate the effects of different devices, participants' characteristics, and testing protocols on the measured spinal stiffness.

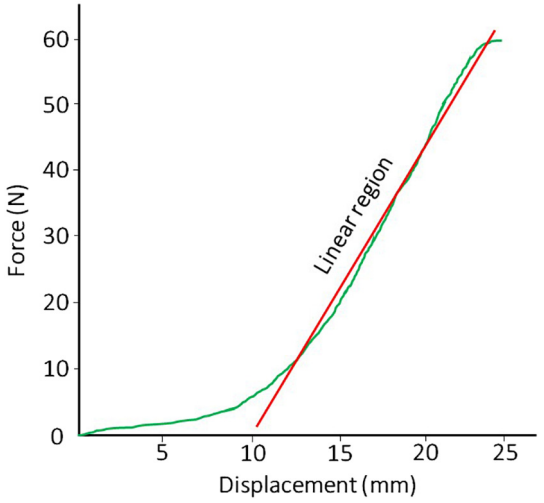

Fig 1. *A typical force-displacement curve obtained from a thoracic or lumbar vertebra during an instrumented spinal stiffness assessment. Although there is no consensus in the literature, 2 common methods have been used to estimate the global and terminal spinal stiffness coefficients.[6] Global spinal stiffness is estimated from the slope of the linear region on a force-displacement (F-D) curve. This coefficient represents the stiffness of underlying tissues throughout the indentation[6] or the tissue dynamics in response to indentation force.[8] Terminal spinal stiffness is estimated from the final loading force and the overall displacement of the indenter and indicates the overall bulk response.[8]*

The purpose of this study was to describe the correlations between individual characteristics (ie, anthropometric data, sex, and age) and spinal stiffness as measured by different spinal stiffness measurement devices in individuals with and without back pain. This goal was achieved by conducting secondary analyses of 3 data sets collected previously using 3 different devices, in 2 spinal regions, in a total of 5 separate cross-sectional studies. It was hypothesized that the correlation between individual characteristics and spinal stiffness would vary greatly between data sets, whereas potentially important individual characteristics would be identified. Given the increasing usage of instrumented spinal stiffness measurement in research and its potential as an objective outcome in clinical settings, understanding its variations or similarities would be of great importance in developing standardized protocols and testing recommendations.

Methods

Data Set Presentation

Secondary analyses of data from 5 independent cross-sectional studies were conducted. Data sets A and B originated from 2 separate studies, whereas data set C comprised 3 studies that were conducted using the same protocol. Details for each data set are presented in Table 1,[7,8,15,19-24] and pictures of each testing device are included in Figure 2. Scientific or ethical review for each original study was approved by the respective university's human research ethics committee, and approval for secondary analyses was obtained when required (Table 1). Individual studies were conducted in accordance with the Helsinki Declaration of 1975. All participants provided their informed and written consent at the stage of the original study according to the ethics approval. These studies were similar in that they all investigated adults, with and without back pain, using a load-controlled indenter device to objectively measure spinal stiffness. Individuals' characteristics (weight, height, BMI, age, and sex) were included in each study, and data set A also included physiological measurements (free-standing height, sitting height, waist circumference, waist-to-height ratio, and waist posteroanterior diameter). The spinal levels assessed, the landmark identification procedure, and the applied load and velocity used to assess spinal stiffness varied between studies (Table 1). Although the theoretical definitions for global and terminal spinal stiffness were the same across the studies, the exact calculation was specific to each data set.

Statistical Analysis

A standardized analysis protocol was established whereby data sets were initially checked for pertinent assumptions that included normality, outliers, and linearity, at the individual variable level. A descriptive analysis was first conducted including means and standard deviations (SD) for parametric data or median and interquartile range (IQR) for nonparametric data. Statistical comparisons between data sets were not conducted because ethics certifications did not allow sharing of data between institutions.

Because spinal stiffness values in men and women were normally distributed in all data sets, *t* tests for independent samples were conducted to compare spinal stiffness between men and women. The Pearson correlation coefficient (r) or its estimated value (r_e) from Kendall's τ rank correlation coefficients (for nonparametric data) was computed to quantify the strength of correlation between spinal stiffness and participants' characteristics (anthropometric, age, and sex). The strength of the correlations was evaluated as "strong" ($r \geq 0.70$), "good" ($0.50 \leq r < 0.70$), "moderate" ($0.30 \leq r < 0.50$), or "poor" ($r < 0.30$).[25] Bias-corrected bootstrapping (1000 bootstrap samples) was used to construct 95% confidence intervals for all correlation coefficients. SPSS Statistics for Windows (IBM, Armonk, New York) was used for all analyses (version 24.0 for data set A, version 21.0 for data set B, version 22.0 for data set C), and statistical significance was set at $P \leq .05$.

Results

Descriptive Analysis of Participants' Characteristics

Participant characteristics for each data set are reported in Table 2. The 3 data sets included participants who reported and did not report back pain. Data sets A and C were used to compare participants reporting at least 1 day of LBP in the past week with participants not reporting a LBP episode within the past week. Data set B was used for comparing participants reporting constant or recurrent thoracic pain for at least the past 3 months (with or without an episode in the past week) with participants without significant pain in the thoracic region for the past year. A total of 288 (146 female, 140 male) participants were included across the 3 study sites. Age and sex ratios differed across the data sets, and this disparity was pronounced when participants were categorized based on the presence or absence of back pain. Anthropometric characteristics (weight, height, and BMI) were consistent among the 3 data sets.

Spinal Stiffness: Descriptive Analysis

Table 3 outlines global and terminal spinal stiffness for each spinal level evaluated in the 3 data sets. Although comparisons between data sets could not be conducted using statistical analyses because of differences in protocols, it can be observed that spinal stiffness values varied greatly between studies. Complete analyses, including effects of spinal levels and back pain on spinal stiffness value, can be found elsewhere for data set A,[19] data set B[26] (article currently under review), and data set C.[7,8,15]

Correlations Between Spinal Stiffness and Individual Characteristics

Tables 4 and 5 outline the correlations between individual characteristics and terminal and global spinal stiffness, respectively. Overall, terminal and global spinal stiffness at specific levels of the spine appears to be correlated with some individual characteristics; however, the pattern of correlations is rarely consistent among the 3 data sets.

Age. No significant correlation between terminal or global stiffness and age was observed in any of the 3 data sets (all P values $> .05$).

Sex. *t* Tests revealed significantly lower spinal stiffness (global and terminal spinal stiffness coefficients) in women than in men in the thoracic spine (data set B). This analysis was significant for all spinal levels (T5 to T8) in participants with chronic thoracic pain (P values $\leq .04$) and when all participants were grouped (P values $\leq .01$). The mean difference in spinal stiffness between women and

Table 1. *Method Details for 3 Data Sets Included for Secondary Analysis in the Present Paper*

Information	Data Set A	Data Set B	Data Set C
Publication status	Published[19]	Published[26]	Published[7,8,15]
Study location	Macquarie University of Sydney, Sydney, NSW, Australia	Université du Québec à Trois-Rivières, Trois-Rivières, QC, Canada	University of Alberta, Edmonton, AB, Canada
Ethics board	Human Research Ethics Committee (HREC [Medical Sciences]) of Macquarie University, Australia	Université du Québec à Trois-Rivières Human Research Ethics Committee	• Human Research Ethics Board - Health Panel and Biomedical Panel, University of Alberta • Human Subjects Ethics Subcommittee at PolyU
Ethics certification number and approval date	5201600008, approved April 24, 2016	CER-16-220-07.04, approved February 10, 2016	• Pro00026307, approved November 29, 2011 • Pro00027069. approved August 6, 2013 • HSEARS20170817005, approved August 17, 2017 (for secondary analysis by PolyU)
Study start and completion months	May to June 2016	April to December 2016	December 2012 to September 2014
Number of participants	84 (20 without LBP/64 with LBP)	75 (25 healthy/50 with chronic thoracic pain)	129 (85 without LBP/44 with current LBP)
Inclusion criteria	Adults (≥18 y) with or without spinal pain	Adults (18-60 y) either healthy (no report of thoracic pain for the past year or with chronic thoracic pain (reporting thoracic pain for at least 3 mo; however, pain at study start was not required)	Adults (18-60 y) either healthy (asymptomatic) or with nonspecific LBP
Exclusion criteria	Unable to lie prone for ≥20 min, late pregnancy, head/neck/thoraco-abdominal or spine surgery within the past 4 wk, severe respiratory condition that precludes lying prone, inability to hold breath for 10 s	Diagnosed visceral condition that could refer pain to the chest wall	Asymptomatic individuals had to report no current LBP or an ongoing LBP intensity <1 on a 0-10 NPRS and did not have to report any LBP-related sick leave in the past 12 mo
Questionnaires completed	Web-based characteristic questionnaire (author created) to determine participant sex, age, recent LBP history	1. Characteristic questionnaire (author created) to determine participant sex, age, weight, and height 2. Chronic thoracic pain participants rated their pain intensity (max, min, and mean) in the past 3 mo as well as current pain (0-100 NPRS)	1. Characteristic questionnaire (author created) to determine the participant's age, sex, height, weight and LBP history at baseline 2. All participants rated their current LBP intensity on an 11-point NPRS
Baseline physical assessment	Free-standing height (cm), sitting height (cm), weight (kg), waist circumference (cm), waist posteroanterior diameter (cm)	No	No

(continued on next page)

Table 1. (*continued*)

Information	Data Set A	Data Set B	Data Set C
Description of testing protocol	VerteTrack (VibeDx Diagnostic Corp., Edmonton, AB, Canada) applied a preselected vertical load (increments of 10 N with a maximum of 60 N) using weight plates. The load was applied in a continuous manner over the spine by a rolling system. The indenter apparatus consisted of a rod suspended within a linear bearing to permit near-frictionless vertical translation and an indentation roller comprising 2 circular plastic disks (diameter 70 mm, width 15 mm). The indentation roller was moved in the X (longitudinal, superior-inferior), Y (transverse, left-right), and Z (vertical, posteroanterior) axes by a stepping motor system (resolution = 0.007 mm) (Stepperonline.com, China). The vertical position of the indenter relative to the frame was measured with a string potentiometer that provides real-time feedback to the control system (resolution = 0.020 mm) (TE Connectivity, USA). A more comprehensive overview of this device has been published elsewhere.[19]	An apparatus using a servo-controlled linear actuator motor (Linear Motor Series P01-48x360, LinMot Inc., Zurich, Switzerland). The device indenter (θ = 18 mm) was manually positioned over the targeted spinous process. The indenter gradually (18 N/s) applied a 45-N load over the targeted spinous process following a 5-N preload application. The indenter displacement and load were recorded using LinMot-Talk 5.1 (LinMot Inc., Elkhorn, WI) at a frequency of 135 Hz. Four experimental trials were performed for each spinal level (T5, T6, T7, and T8), and the average of the last 3 trials was used for data analysis. Participants were instructed to hold their breath at the end of normal exhalation during each spinal stiffness assessment. A complete description of the apparatus and its security features can be found elsewhere.[20]	A computer-controlled mechanical indentation device that applied an anteroposterior force to the participant's spinous process. The device comprised a motor (Dual Motion Motor, Waterbury, CT) to move an indenter probe, a rotary encoder (Dual Motion Motor) to quantify probe displacement, and a compression-tension load cell (Entran, Fairfield, NJ) to measure applied loading force. The device has demonstrated high accuracy[21] and excellent within- and between-day test-retest reliability measuring stiffness in people with and without LBP.[15] Custom-written LabVIEW software (National Instruments, Austin, TX) was used to control the loading speed (2.0 mm/s) of the probe and to collect force and displacement signals. All indentation was performed with force applied vertically at the contact site. Three experimental indentations were then performed with a preload of 5 N and with a target load of 60 N. Participants were instructed to hold their breath at the end of normal exhalation throughout the indentation process.
Method to identify spinal levels	Through a combination of bony landmarks and motion palpation[22]	Through a combination of bony landmarks[23,24]	Ultrasound
Loading profile	Incrementally increasing by 10 N from 0 to 60 N	Continuously increased from 5 to 45 N at 18 N/s	The indenter was lowered at 2 mm/s with a 1-s pause at a preload of 5 N, and then continued to advance until the applied force reached 60 N. The indenter paused at 60 N for 1 s before its withdrawal.
Spinal levels evaluated	L1, L2, L3	T5, T6, T7, T8	L3
Calculation of global spinal stiffness coefficient	Slope of the best straight line fitting the force displacement curve between 10 and 60 N	Slope of the best straight line fitting the force displacement curve between 10 and 45 N	Slope of the best straight line fitting the force displacement curve between 5 and 60 N
Calculation of terminal spinal stiffness coefficient	Ratio of maximal applied force (60 N) to maximal resultant displacement (mm).	Ratio of variation of load to variation of displacement between 10 and 45 N.	Ratio of variation of load to variation of displacement between 5 and 60 N.

LBP, low back pain; *NPRS*, numeric pain rating scale; *PolyU*, The Hong Kong Polytechnic University.

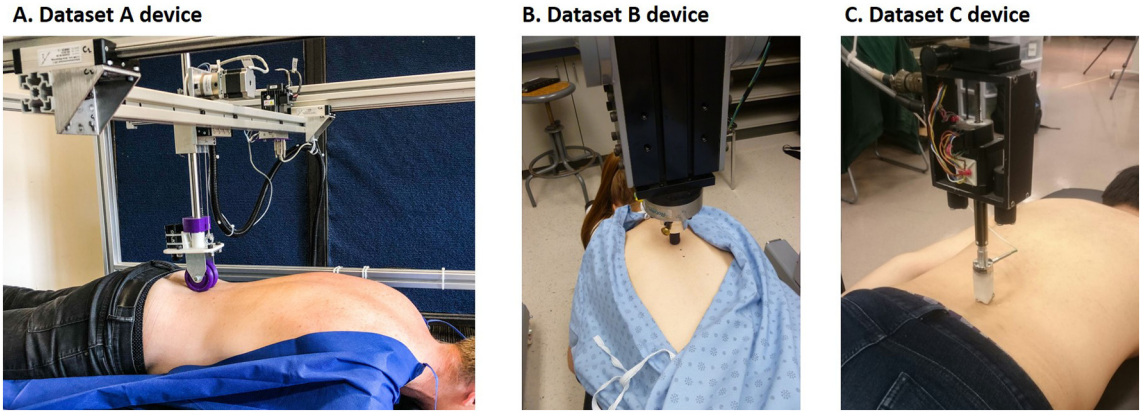

Fig 2. *Devices used in the studies providing data sets A, B, and C. Spinal stiffness was determined based on the load displacement curve obtained by each device; however, the protocol used differed between studies.*

men ranged between 0.88 and 1.41 N/mm. Regarding the lumbar spine, data set A revealed significantly lower global spinal stiffness in women at L3 and L5, but not at L1. This analysis was significant when all participants were grouped and when only participants with ≥1 day of LBP in the past week were evaluated (P values < .05). No significant difference in global spinal stiffness was observed in participants without LBP in the past week and in terminal spinal stiffness (all P values > .05). There was a mean difference in spinal stiffness between women and men ranging between 0.09 and 0.12 N/mm. Similar to data set A, data set C revealed significantly lower spinal stiffness at L3 in women than in men when all participants were grouped (terminal stiffness: $t(127) = 2.98$, $P = .04$; global stiffness: $t(127) = 3.05$, $P = .03$) and when only participants with ≥1 day of LBP in the past week (terminal stiffness: $t(42) = 3.00$, $P = .01$; global stiffness: $t(42) = 2.94$, $P = .01$) were evaluated.

Height. Data set C revealed significant but poor correlations between L3 spinal stiffness and height (terminal stiffness: $r = 0.18$ [0.01, 0.34]; global stiffness: $r = 0.21$ [0.04, 0.37]) among all participants. The correlation was of moderate strength when only participants with ≥1 day of LBP in the past week were evaluated (terminal stiffness: $r = 0.33$ [0.04, 0.57]; global stiffness: $r = 0.37$ [0.08, 0.60]). In data set A, height was significantly correlated with terminal spinal stiffness only at L5 in participants without LBP ($r = 0.49$ [0.15, 0.78]) and with global spinal stiffness at L3 when all participants were grouped regardless of pain status ($r = 0.22$ [–0.01, 0.40]). Overall, height was moderately to strongly correlated with thoracic terminal and global spinal stiffness. Specifically, except for T6 in individuals with and without chronic thoracic pain, terminal spinal stiffness was significantly correlated with height at all spinal levels ($0.18 \leq r_e \leq 0.58$). Similarly, height was moderately correlated with global spinal stiffness at all spinal levels when all participants were grouped ($0.31 \leq r \leq 0.33$) and in individuals without chronic thoracic pain ($0.45 \leq r \leq 0.55$). In participants with chronic thoracic pain, only T5 was significantly correlated with global spinal stiffness ($r = 0.33$ [0.02, 0.61]). Overall, these correlations indicate that an increase in spinal stiffness value is associated with an increase in body height.

Weight. Weight was significantly correlated (poor to moderate strength) with spinal stiffness at all spinal levels when all participants were grouped in data set B ($0.26 \leq r \leq 0.41$). In participants without chronic thoracic pain, these variables were moderately to strongly correlated at 3 of the 4 spinal levels ($0.41 \leq r \leq 0.56$). In individuals with chronic thoracic pain, significant correlations were observed only at T5 and T6 ($0.37 \leq r \leq 0.41$). For the lumbar spine, although data set C did not reveal any significant correlation (all P values >.05), data set A revealed only a poor inverse correlation between weight and L5 terminal stiffness in participants with ≥1 day of LBP in the past week ($r = –0.26$ [–0.46, 0.01]), indicating that heavier individuals with ≥1 day of LBP in the past week seemed to have lower L5 lumbar terminal stiffness values.

Body Mass Index. Data set C revealed a poor negative correlation between L3 spinal stiffness and BMI: all participants (terminal stiffness: $r = –0.24$ [–0.40, –0.08]; global stiffness: $r = –0.25$ [–0.39, 0.07]), participants without LBP in the past week (terminal stiffness: $r = –0.22$ [–0.44, –0.04]; global stiffness: $r = –0.25$ [–0.41, –0.01]), and participants with ≥1 day of LBP in the past week (terminal stiffness: $r = -0.22$ [–0.68, –0.11]; global stiffness: $r = –0.39$ [–0.49, –0.08]). In data set A, L5 spinal stiffness was poorly to moderately correlated with terminal and global spinal stiffness when all participants were grouped (terminal stiffness: $r = –0.35$ [–0.54, –0.14]; global stiffness: $r = –0.25$ [–0.41, –0.07]) and when only individuals reporting ≥1 day of LBP in the past week were evaluated (terminal stiffness: $r = –0.37$ [–0.57, –0.13]; global stiffness: $r = –0.27$ [–0.45, –0.08]). For the thoracic spine, correlations were inconsistent. T6 was moderately correlated with global ($r = 0.34$ [0.05, 0.58]) and terminal ($r = 0.34$ [0.01, 0.58]) spinal stiffness in participants reporting chronic thoracic pain and poorly

Table 2. *Participants' Characteristics per Data Set*

	Data Set A			Data Set B			Data Set C		
Characteristic	All (n = 84)	0 d of LBP in Past Week (n = 20)	≥1 d of LBP in Past Week (n = 64)	All (n = 75)	Not Reporting Chronic Thoracic Pain (n = 25)	Reporting Chronic Thoracic Pain (n = 50)	All (n = 129)	0 d of LBP in Past Week (n = 85)	≥1 d of LBP in Past Week (n = 44)
Men:women	54:30	16:4	38:26	37:38	13:12	24:26	51:78	38:47	13:31
Age (y)	Median: 23 IQR: 3	Median: 23 IQR: 6	Median: 23 IQR: 3	Median: 27 IQR: 9	Median: 25 IQR: 7	Median: 27 IQR: 12	Mean: 29.3 SD: 10.1	Mean: 28.4 SD: 10.0	Mean: 31.0 SD: 10.3
Weight (kg)	Mean: 72.0 SD: 15.8	Mean: 72.8 SD: 9.2	Mean: 71.8 SD: 17.5	Median: 69.17 IQR: 16.77	Mean: 69.63 SD: 11.24	Median: 68.95 IQR: 15.88	Mean: 69.0 SD: 14.5	Mean: 67.9 SD: 15.0	Mean: 71.1 SD: 13.2
Standing height (m)	Mean: 1.72 SD: 0.95	Mean: 1.73 SD: 0.82	Mean: 1.71 SD: 0.99	Mean: 1.71 SD: 0.10	Mean: 1.72 SD: 0.11	Mean: 1.71 SD: 0.09	Mean: 1.7 SD: 0.1	Mean: 1.7 SD: 0.1	Mean: 1.7 SD: 0.1
Body mass index (kg/m^2)	Mean: 24.3 SD: 3.9	Mean: 24.39 SD: 2.28	Mean: 24.28 SD: 4.35	Mean: 23.94 SD: 3.60	Mean: 23.50 SD: 2.48	Mean: 24.17 SD: 4.07	Mean: 23.4 SD: 4.4	Mean: 22.7 SD: 4.4	Mean: 24.6 SD: 4.0
Seating height (cm)	Mean: 90.8 SD: 5.4	Mean: 91.3 SD: 4.9	Mean: 90.7 SD: 5.5	-	-	-	-	-	-
Waist circumference (cm)	Mean: 84.2 SD: 10.4	Mean: 83.4 SD: 7.4	Mean: 84.5 SD: 11.2	-	-	-	-	-	-
Waist posteroanterior diameter (cm)	Mean: 18.7 SD: 3.4	Mean: 18.1 SD: 3.1	Mean: 18.9 SD: 3.5	-	-	-	-	-	-
Waist-to-height ratio	Mean: 0.49 SD: 0.06	Mean: 0.48 SD: 0.05	Mean: 0.49 SD: 0.06	-	-	-	-	-	-

IQR, interquartile range; *LBP,* low back pain; *SD*, standard deviation;

Table 3. *Global and Terminal Spinal Stiffness per Data Set*

	Data Set A				Data Set B				Data Set C			
Stiffness Coefficient	Spinal Level	All (n = 84)	Men (n = 54) vs Women (n = 30)	0 d of LBP in Past Week (n = 20) vs ≥1 d of LBP in Past Week (n = 64)	Spinal Level	All (n = 75)	Men (n = 37) vs Women (n = 38)	Not Reporting Chronic Thoracic Pain (n = 25) vs Reporting Chronic Thoracic Pain (n = 50)	Spinal Level	All (n = 129)	Men (n = 51) vs Women (n = 78)	0 d of LBP in Past Week (n = 85) vs ≥ 1 d of LBP in Past Week (n = 44)
Global	L1	1.14 ± 0.22	1.16 ± 0.22 vs 1.09 ± 0.22	1.11 ± 0.20 vs 1.15 ± 0.23	T5	7.87 ± 1.59	8.43 ± 1.30 vs 7.33 ± 1.68	8.23 ± 1.22 vs 7.69 ± 1.73	L3	5.70 ± 1.26	6.11 ±1.36 vs 5.44 ± 1.11	5.71 ± 1.24 vs 5.71 ± 1.24
	L3	1.14 ± 0.21	1.17 ± 0.22 vs 1.08 ± 0.20	1.13 ± 0.22 vs 1.14 ± 0.22	T6	8.13 ± 1.70	8.71 ± 1.73 vs 7.56 ± 1.45	8.55 ± 1.68 vs 7.91 ± 1.68	-	-	-	-
	L5	1.16 ± 0.20	1.18 ± 0.19 vs 1.11 ± 0.22	1.15 ± 0.19 vs 1.16 ± 0.21	T7	8.32 ± 1.70	8.88 ± 1.65 vs 7.78 ± 1.58	8.79 ± 1.53 vs 8.08 ± 1.74	-	-	-	-
	-	-	-	-	T8	8.22 ± 1.53	8.68 ± 1.66 vs 7.76 ± 1.26	8.78 ± 1.32 vs 7.93 ± 1.56	-	-	-	-
Terminal	L1	1.04 ± 0.17	1.07 ± 0.17 vs 0.99 ± 0.17	1.02 ± 0.13 vs 1.05 ± 0.18	T5	8.11 ± 1.61	8.69 ± 1.28 vs 7.56 ± 1.71	8.54 ± 1.25 vs 7.90 ± 1.73	L3	5.68 ± 1.29	5.58 ±1.18 vs 5.01 ± 0.98	5.22 ± 1.07 vs 5.26 ± 1.15
	L3	1.02 ± 0.16	1.04 ± 0.15 vs 0.99 ± 0.17	1.00 ± 0.14 vs 1.03 ± 0.16	T6	8.36 ± 1.72	8.69 ± 1.78 vs 7.79 ± 1.46	8.86 ± 1.70 vs 8.11 ± 1.69	-	-	-	-
	L5	1.00 ± 0.15	0.99 ± 0.15 vs 0.99 ± 0.16	0.98 ± 0.13 vs 1.01 ± 0.16	T7	8.50 ± 1.76	9.07 ± 1.77 vs 7.96 ± 1.59	9.02 ± 1.56 vs 8.25 ± 1.81	-	-	-	-
	-	-	-	-	T8	8.39 ± 1.57	8.83 ± 1.70 vs 7.95 ± 1.31	8.99 ± 1.37 vs 8.08 ± 1.58	-	-	-	-

LBP, low back pain.
Results are expressed as the mean ± standard deviation.

Table 4. *Correlations Between Terminal Spinal Stiffness and Individual Characteristics*

	Data Set A				Data Set B				Data Set C			
Characteristic	Spinal Level	All (n = 84)	0 d of LBP in Past Week (n = 20)	≥1 d of LBP in Past Week (n = 64)	Spinal Level	All (n = 75)	Not Reporting Chronic Thoracic Pain (n = 25)	Reporting Chronic Thoracic Pain (n = 50)	Spinal Level	All (n = 129)	0 d of LBP in Past Week (n = 85)	≥1 d of LBP in Past Week (n = 44)
Age	L1	r_e = 0.07 (–0.12, 0.24) P = .38	r_e = 0.09 (–0.39, 0.50) P = .60	r_e = 0.06 (–0.13, 0.26) P = .51	T5	r_e = 0.01 (–0.23, 0.28) P = .93	r_e = –0.11 (–0.54, 0.37) P = .62	r_e = 0.05 (–0.30, 0.35) P = .76	L3	r = 0.04 (–0.14, 0.21) P = .54	r = 0.09 (–0.12, 0.30) P = .22	r = –0.09 (–0.38, 0.21) P = .39
	L3	r_e = 0.05 (–0.13, 0.22) P = .51	r_e = 0.108 (–0.28, 0.49) P = .51	r_e = 0.03 (–0.18, 0.24) P = .71	T6	r_e = 0.00 (–0.24, 0.24) P = .99	r_e = –0.11 (–0.60, 0.41) P = .62	r_e = 0.07 (–0.24, 0.33) P = .67	-	-	-	-
	L5	r_e = –0.02 (–0.20, 0.15) P = .76	r_e = 0.03 (–0.34, 0.38) P = .85	r_e = –0.05 (–0.23, 0.15) P = .61	T7	r_e = 0.02 (–0.24, 0.28) P = .87	r_e = 0.19 (–0.33, 0.61) P = .41	r_e = –0.02 (–0.38, 0.31) P = .89	-	-	-	-
	-	-	-	-	T8	r_e = –0.10 (–0.33, 0.15) P = .44	r_e = –0.08 (–0.46, 0.34) P = .72	r_e = –0.08 (–0.41, 0.26) P = .62	-	-	-	-
Sex [a]	L1	t(78) = 1.89 P = .06	t(17) = 0.58 P = .57	t(59) = 2.00 P = .05	T5	t(73) = 3.23 P = .002	t(23) = 0.93 P = .36	t(48) = 3.17 P = .003	L3	t(127) = 2.98 P = .04	t(83) = 1.68 P = .10	t(42) = 3.00 P = .01
	L3	t(78) = 1.33 P = .19	t(17) = 0.88 P = .39	t(59) = 1.25 P = .22	T6	t(73) = 3.06 P = .003	t(23) = 1.78 P = .09	t(48) = 2.44 P = .02	-	-	-	-
	L5	t(78) = 0.67 P = .50	t(17) = 0.91 P = .38	t(59) = 0.58 P = .56	T7	t(73) = 2.86 P = .005	t(23) = 1.73 P = .10	t(48) = 2.25 P = .03	-	-	-	-
	-	-	-	-	T8	t(73) = 2.52 P = .01	t(23) = 1.38 P = .18	t(48) = 2.09 P = .04	-	-	-	-
Standing height	L1	r = 0.21 (0.01, 0.40) P = .06 n = 82	r = 0.35 (–0.05, 0.70) P = .14	r = 0.19 (–0.06, 0.41) P = .15	T5	r_e = 0.48 (0.16, 0.73) P = .01	r = 0.45 (0.05, 0.75) P = .02	r = 0.33 (0.03, 0.61) P = .02	L3	r = 0.18 (0.01, 0.34) P = .04	r = 0.11 (0.10, 0.32) P = .31	r = 0.33 (0.04, 0.57) P = .03
	L3	r = 0.15 (–0.06, 0.36), P = .17 n = 82	r = 0.39 (0.02, 0.73) P = .09	r = 0.11 (–0.19, 0.38) P = .42	T6	r_e = 0.49 (0.18, 0.71) P = .01	r = 0.30 (–0.20, 0.68) P = .14	r = 0.18 (–0.08, 0.45) P = .22	-	-	-	-

	L5	r = 0.13 (–0.12, 0.36) P = .26 n = 82	r = 0.49 (0.15, 0.78) P = .03	r = 0.06, (–0.23, 0.35) P = .64	T7	r_e = 0.51 (0.21, 0.75) P = .003	r = 0.58 (0.35, 0.77) P = .003	r = 0.29 (–0.01, 0.56) P = .045	-	-	-	-
	-	-	-	-	T8	r_e = 0.45 (0.11, 0.70) P = .01	r = 0.46 (0.15, 0.68) P = .02	r = 0.24 (–0.08, 0.51) P = .10	-	-	-	-
Sitting height	L1	r = 0.16 (–0.04, 0.36) P = .16 n = 80	r = 0.06 (–0.48, 0.51) P = .80	r = 0.19 (–0.04, 0.40) P = .15	T5	-	-	-	L3	-	-	-
	L3	r = 0.06 (–0.17, 0.28), P = .63 n = 80	r = 0.06 (–0.48, 0.50) P = .81	r = 0.06 (–0.18, 0.31) P = .66	T6	-	-	-	-	-	-	-
	L5	r = –0.01 (–0.25, 0.22), P = .90 n = 80	r = 0.11 (–0.54, 0.59) P = .65	r = –0.036 (–0.28, 0.22) P = .78	T7	-	-	-	-	-	-	-
	-	-	-	-	T8	-	-	-	-	-	-	-
Weight	L1	r = 0.1 (–0.11, 0.32) P = .35 n = 82	r = 0.35 (–0.29, 0.71) P = .13	r = 0.07 (–0.17, 0.31) P = .57	T5	r_e = 0.32 (0.08, 0.52) P = .01	r = 0.42 (0.07, 0.70) P = .04	r_e = 0.40 (0.14, 0.66) P = .01	L3	r = –0.10 (–0.27, 0.07) P = .08	r = –0.13 (–0.33, 0.09) P = .08	r = – 0.08 (–0.36, 0.23) P = .63
	L3	r = –0.03 (–0.26, 0.21) P = .78 n = 82	r = 0.42 (–0.26, 0.78) P = .06	r = –0.09 (–0.33, 0.17) P = .47	T6	r_e = 0.41 (0.19, 0.61) P = .001	r = 0.10 (–0.29, 0.45) P = .62	r_e = 0.37 (0.08, 0.62) P = .02	-	-	-	-
	L5	r = –0.21 (–0.39, 0.05) P = .06 n = 82	r = 0.21 (–0.37, 0.67) P = .39	r = –0.26 (–0.46, 0.01) P = .04	T7	r_e = 0.28 (0.07, 0.48) P = .02	r = 0.56 (0.19, 0.80) P = .003	r_e = 0.22 (–0.05, 0.46) P = .16	-	-	-	-
	-	-	-	-	T8	r_e = 0.26 (0.01, 0.49) P = .04	r = 0.46 (0.11, 0.69) P = .02	r_e = 0.23 (-0.07, 0.52) P = .15	-	-	-	-
Body mass index	L1	r = 0.01 (–0.23, 0.23)	r = 0.12 (–0.65, 0.61)	r = –0.01 (–0.22, 0.25)	T5	r_e = 0.16 (–0.08, 0.41)	r = –0.22 (–0.64, 0.28)	r = 0.18 (–0.08, 0.42)	L3	r = –0.25 (–0.40, –0.08)	r = –0.25 (–0.44, –0.04)	r = –0.39 (–0.68, –0.11)

(continued on next page)

Table 4. (*continued*)

	Data Set A				Data Set B				Data Set C			
Characteristic	Spinal Level	All (n = 84)	0 d of LBP in Past Week (n = 20)	≥1 d of LBP in Past Week (n = 64)	Spinal Level	All (n = 75)	Not Reporting Chronic Thoracic Pain (n = 25)	Reporting Chronic Thoracic Pain (n = 50)	Spinal Level	All (n = 129)	0 d of LBP in Past Week (n = 85)	≥1 d of LBP in Past Week (n = 44)
		P = .96 n = 82	P = .63	P = .95		P = .19	P = .30	P = .21		P < .001	P = .001	P = .01
	L3	r = –0.14 (–0.35, 0.08) P = .20 n = 82	r = 0.17 (–0.64, 0.71) P = .48	r = –0.19 (–0.39, 0.04) P = .14	T6	r_e = 0.23 (–0.02, 0.47) P = .06	r = 0.16 (–0.33, 0.66) P = .43	r = 0.34 (0.01, 0.58) P = .02	-	-	-	-
	L5	r = –0.35 (–0.54, –0.14) P = .001 n = 82	r = –0.21 (–0.84, 0.47) P = .37	r = –0.37 (–0.56, –0.13) P = .003	T7	r_e = 0.05 (–0.18, 0.28) P = .70	r = 0.15 (–0.30, 0.57) P = .48	r = 0.01 (–0.28, 0.27) P = .97	-	-	-	-
	-	-	-	-	T8	r_e = 0.12 (–0.13, 0.35) P = .35	r = 0.04 (–0.29, 0.39) P = .87	r = 0.08 (–0.22, 0.40) P = .59	-	-	-	-
Waist circumference	L1	r = 0.04 (–0.21, 0.28) P = .72 n = 82	r = 0.28 (–0.53, 0.68) P = .24	r = –0.01 (–0.23, 0.22) P = .97	T5	-	-	-	L3	-	-	-
	L3	r = –0.05 (–0.32, 0.21) P = .63 n = 82	r = 0.34 (–0.50, 0.76) P = .14	r = –0.13 (–0.35, 0.10) P = .32	T6	-	-	-	-	-	-	-
	L5	r = –0.22 (–0.44, 0.04) P = .049 n = 82	r = 0.11 (–0.58, 0.66) P = .64	r = –0.28 (–0.48, –0.05) P = .03	T7	-	-	-	-	-	-	-
	-	-	-	-	T8	-	-	-	-	-	-	-
Waist Postero-anterior diameter	L1	r = 0.02 (–0.23, 0.25) P = .88 n = 82	r = 0.34 (–0.29, 0.71) P = .14	r = –0.07 (–0.32, 0.19) P = .60	T5	-	-	-	L3	-	-	-

	L3	r = –0.05 (–0.29, 0.2) P = .65 n = 82	r = 0.39 (–0.36, 0.76) P = .09	r = –0.16 (–0.39, 0.11) P = .20	T6	-	-	-		-	-	-
	L5	r = –0.2 (–0.42, 0.06) P = .08 n = 82	r = 0.30 (–0.33, 0.80) P = .20	r = –0.32 (–0.54, –0.03) P = .01	T7	-	-	-	-	-	-	-
	-	-	-	-	T8	-	-	-	-	-	-	-
Waist-to-height ratio	L1	r = –0.06 (–0.31, 0.18) P = .59 n = 82	r = 0.07 (–0.57, 0.52) P = .76	r = –0.10 (–0.38, 0.19) P = .46	T5	-	-	-	L3	-	-	-
	L3	r = –0.13 (–0.38, 0.11) P = .24 n = 82	r = 0.11 (–0.57, 0.60) P = .65	r = –0.19 (–0.45, 0.09) P = .13	T6	-	-	-	-	-	-	-
	L5	r = –0.29 (–0.51, –0.06) P = .01 n = 82	r = –0.14 (–0.70, 0.43) P = .54	r = –0.33 (–0.55, –0.07) P = .01	T7	-	-	-	-	-	-	-
	-	-	-	-	T8	-	-	-	-	-	-	-

LBP, low back pain.

[a] significant difference implies lower spinal stiffness in women compared with men.

correlated with global spinal stiffness when all participants were grouped (r = 0.25 [0.00, 0.48]). Moreover, T8 global spinal stiffness was moderately correlated with BMI in healthy participants only (r = 0.47 [0.17, 0.68]).

Other Anthropometric Characteristics. Data set A also included other anthropometric measures, some of which were significantly correlated with spinal stiffness (Table 5). Interestingly all significant correlations were observed either when all participants were grouped or when only individuals with ≥1 day of LBP in the past week were evaluated. Waist circumference had significant reverse correlations with the terminal spinal stiffness of L5 when all participants were grouped (r = –0.22 [–0.44, –0.04]) and among individuals with ≥1 day of LBP in the past week (r = –0.28 [–0.48, –0.05]). Waist posteroanterior diameter had a significant inverse correlation of moderate strength with L5 terminal spinal stiffness in participants with ≥1 day of LBP in the past week (r = –0.32 [–0.54, –0.03]). L5 global and terminal spinal stiffness was significantly correlated (moderate strength) with the waist-to-height ratio when all participants were grouped (terminal coefficient = –0.29 [–0.51, –0.06]; global coefficient = –0.26 [–0.41, –0.06]) and when only individuals with ≥1 day of LBP in the past week were evaluated (terminal coefficient = –0.33 [–0.55, –0.07]; global coefficient = –0.31 [–0.48, –0.31]). Sitting height was not significantly correlated with spinal stiffness, and waist circumference and waist posteroanterior diameter were not significantly correlated with global spinal stiffness at any of the lumbar spinal levels (all P values > .05).

Discussion

This secondary analysis of 3 data sets independently collected at different universities was conducted to identify whether individuals' characteristics (including anthropometric, age, and sex) are associated with spinal stiffness values. Similarly to this investigation, prior studies have reported heterogeneous findings using different devices and protocols in different settings. As a result, although some studies report significant correlations between spinal stiffness and participant age,[9] sex,[9-11] weight,[10-12] skinfold,[12] and BMI,[10-13] others have found no correlation between spinal stiffness and similar individual characteristics, such as age,[9,11,14-17] sex,[14,16,17] weight,[9,14,16,17] height,[11,14-17] and BMI.[18] The current study is the first to conduct identical statistical analyses on data acquired using different testing protocols and devices. Height and BMI were significantly correlated with spinal stiffness in 2 or 3 of the data sets, and the latter significantly differed between the sexes. Our explanation of why some studies may have failed to identify these correlations/differences, and why other individual characteristics (eg, weight and age) had inconsistent or nonsignificant correlations, is discussed below.

Similarly to previous studies,[10-13] data set A revealed a significant negative relationship between spinal stiffness and weight and between spinal stiffness and BMI. Data set C also revealed a significant negative correlation with BMI but not with weight, which has also been previously reported.[11,14-17] Higher body weight and BMI may indicate a thicker layer of subcutaneous tissue and soft tissues at the abdominal or dorsal lumbar region that may increase the compliance of tissue during indentation, yielding lower measured spinal stiffness. This idea is further supported by the negative correlations between waist circumference, or waist-to-height ratio, and spinal stiffness observed in data set A. Viner et al observed negative correlations between skinfold thickness and spinal stiffness, which were significant from L3 to S1 ($-0.53 \leq r \leq -0.71$) but not at L1 and L2.[12] They suggested that participants with greater BMI and skinfold values might have a greater extent of fat distribution around the lower abdomen and pelvis and over the lower spinous processes than around the upper trunk. Results for data set A also align with this assumption; significant correlations were observed at L5 but not at L1 and L3. In contrast to the lumbar spine, data set B suggests a positive correlation between thoracic spinal stiffness and body weight or BMI. This correlation may be explained in that fat is less likely to accumulate in the thoracic region.[27] These opposite correlations observed in the lumbar and the thoracic regions highlight the need to evaluate spinal regions individually and to limit generalization of results between spinal regions.

Previous studies have not reported significant correlations between height and spinal stiffness.[9,14,16,17] In the current study, height was significantly correlated with spinal stiffness in the 3 data sets. These correlations were positive in the 3 data sets but more consistent in data set B (thoracic spine). Vertebral morphology, such as vertebral body height and spinous process length, as well as the magnitude of spine curvatures, is known to be related to individual body height.[28-30] Body height can therefore affect measurement angulation, which could explain the correlation with spinal stiffness measurement. These correlations were positive in the 3 data sets but more consistent in data set B (thoracic spine).

Across the 3 data sets, spinal stiffness was lower in women than in men, a finding that is consistent with previous studies.[9-11] Differences in fat distribution or in weight between women and men may partially explain these results. Women are known to have higher subthoracic and abdominal skinfold thickness, which may increase the compliance of tissue during spinal stiffness measurements and results in lower spinal stiffness values.[27] Further supporting this hypothesis are the results of Snodgrass et al,[9] who found a significant correlation between cervical spine stiffness and sex at C7 but not C2. Interestingly, in all data sets, no significant difference was observed when only participants without back pain were evaluated. Although the reason for this lack of

Table 5. *Correlations Between Global Spinal Stiffness and Individual Characteristics*

	Data Set A				Data Set B				Data Set C			
Characteristic	Spinal Level	All (n = 84)	0 d of LBP in Past Week (n = 20)	≥1 d of LBP in Past Week (n = 64)	Spinal Level	All (n = 75)	Not Reporting Chronic Thoracic Pain (n = 25)	Reporting Chronic Thoracic Pain (n = 50)	Spinal Level	All (n = 129)	0 d of LBP in Past Week (n = 85)	≥ 1 d of LBP in Past Week (n = 44)
Age	L1	r_e = 0.08 (–0.08, 0.24) P = .33	r_e = –0.06 (–0.52, 0.39) P = .72	r_e = 0.13 (–0.10, 0.34) P = .15	T5	r_e = 0.02 (–0.23, 0.29) P = .89	r_e = –0.11 (–0.52, 0.36) P = .62	r_e = 0.06 (–0.29, 0.36) P = .68	L3	r = 0.06 (–0.11, 0.23) P = .31	r = 0.07 (–0.14, 0.28) P = .52	r = –0.04 (–0.33, 0.26) P = .74
	L3	r_e = 0.08 (–0.08, 0.24) P = .31	r_e = –0.09 (–0.46, 0.32) P = .60	r_e = 0.13 (–0.11, 0.33) P = .16	T6	r_e = 0.01 (–0.23, 0.26) P = .95	r_e = –0.12 (–0.59, 0.39) P = .59	r_e = 0.08 (–0.22, 0.37) P = .59	-	-	-	-
	L5	r_e = 0.03 (–0.13, 0.21) P = .70	r_e = –0.10 (–0.52, 0.30) P = .57	r_e = 0.06 (–0.16, 0.29) P = .48	T7	r_e = 0.02 (–0.25, 0.27) P = .89	r_e = 0.10 (–0.43, 0.56 P = .66	r_e = –0.01 (–0.37, 0.32 P = .98	-	-	-	-
	-	-	-	-	T8	r_e = – 0.09 (–0.34, 0.16) P = .49	r_e = –0.04 (–0.44, 0.41) P = .87	r_e = –0.05 (–0.38, 0.27) P = .73	-	-	-	-
Sex [a]	L1	t(78) = 1.69 P = .10	t(17) = 0.50 P = .62	t(59) = 1.91 P = .06	T5	t(73) = 3.15 P = .002	t(23) = 0.85 P = .41	t(48) = 3.11 P = .003	L3	t(127) = 3.05 P = .03	t(83) = 1.75 P = .08	t(42) = 2.94 P = .01
	L3	t(78) = 2.29 P = .02	t(17) = 0.76 P = .46	t(59) = 2.38 P = .02	T6	t(73) = 3.09 P = .003	t(23) = 1.82 P = .08	t(48) = 2.43 P = .02	-	-	-	-
	L5	t(78) = 2.01 P = .048	t(17) = 0.63 P = .54	t(59) = 2.08 P = .04	T7	t(73) = 2.95 P = .004	t(23) = 2.03 P = .05	t(48) = 2.17 P = .04	-	-	-	-
	-	-	-	-	T8	t(73) = 2.71 P = .01	t(23) = 1.53 P = .14	t(48) = 2.22 P = .03	-	-	-	-
Standing height	L1	r = 0.14 (–0.12, 0.38) P = .21 n = 81	r = 0.23 (–0.28, 0.73) P = .34	r = 0.13 (–0.21, 0.44) P = .31	T5	r = 0.31 (0.10, 0.52) P = .01	r = 0.29 (–0.22, 0.66) P = .16	r = 0.33 (0.02, 0.61) P = .02	L3	r = 0.21 (0.04, 0.37) P = .02	r = 0.13 (–0.08, 0.34) P = .23	r = 0.37 (0.08, 0.60) P = .01
	L3	r = 0.22 (–0.01, 0.40) P = .05 n = 81	r = 0.29 (–0.22, 0.75) P = .24	r = 0.20 (–0.06, 0.45) P = .11	T6	r = 0.32 (0.10, 0.49) P = .01	r = 0.55 (0.32, 0.74) P = .01	r = 0.18 (–0.08, 0.44) P = .22	-	-	-	-
	L5	r = 0.20 (–0.01, 0.40) P = .07 n = 81	r = 0.39 (–0.17, 0.78) P = .10	r = 0.16 (–0.10 0.45) P = .20	T7	r = 0.33 (0.12, 0.53) P = .004	r = 0.47 (0.17, 0.68) P = .02	r = 0.27 (–0.03, 0.55) P = .06	-	-	-	-
	-	-	-	-	T8	r = 0.31 (0.08, 0.50)	r = 0.45 (0.05, 0.75)	r = 0.24 (–.07, 0.52)	-	-	-	-

(continued on next page)

Table 5. (*continued*)

	Data Set A				Data Set B				Data Set C			
Characteristic	Spinal Level	All (n = 84)	0 d of LBP in Past Week (n = 20)	≥1 d of LBP in Past Week (n = 64)	Spinal Level	All (n = 75)	Not Reporting Chronic Thoracic Pain (n = 25)	Reporting Chronic Thoracic Pain (n = 50)	Spinal Level	All (n = 129)	0 d of LBP in Past Week (n = 85)	≥ 1 d of LBP in Past Week (n = 44)
						P = .01	*P* = .02	*P* = .09				
Sitting height	L1	*r* = 0.07 (–0.23, 0.35) *P* = .54 n = 80	*r* = 0.09 (–0.48, 0.52) *P* = .73	*r* = 0.07 (–0.21, 0.37) *P* = .58	T5	-	-	-	L3	-	-	-
	L3	*r* = 0.13 (–0.15, 0.39) *P* = .25 n = 80	*r* = 0.14 (–0.39, 0.56) *P* = .59	*r* = 0.13 (–0.13, 0.39) *P* = .31	T6	-	-	-	-	-	-	-
	L5	*r* = 0.07 (–0.21, 0.33), *P* = .55 n = 80	*r* = 0.17 (–0.46, 0.58) *P* = .50	*r* = 0.05 (–0.25, 0.35) *P* = .72	T7	-	-	-	-	-	-	-
	-	-	-	-	T8	-	-	-	-	-	-	-
Weight	L1	*r* = 0.08 (–0.12, 0.27) *P* = .47 n = 81	*r* = 0.25 (–0.37, 0.66) *P* = .29	*r* = 0.06 (–0.18, 0.28) *P* = .62	T5	r_e = 0.31 (0.07, 0.52) *P* = .01	*r* = 0.11 (–0.29, 0.44) *P* = .62	r_e = 0.41 (0.15, 0.66) *P* = .01	L3	*r* = – 0.08 (–0.25, 0.09) *P* = .18	*r* = –0.11 (–0.32, 0.10) *P* = .13	*r* = 0.03 (–0.27, 0.32) *P* = .80
	L3	*r* = 0.05 (–0.13, 0.22) *P* = .64 n = 81	*r* = 0.27 (–0.23, 0.66) *P* = .26	*r* = 0.02 (–0.18, 0.23) *P* = .86	T6	r_e = 0.41 (0.18, 0.61) *P* = .001	*r* = 0.53 (0.17, 0.79) *P* = .01	r_e = 0.37 (0.09, 0.63) *P* = .01	-	-	-	-
	L5	*r* = –0.08 (–0.27, 0.12) *P* = .47 n = 81	*r* = 0.20 (–0.25, 0.69) *P* = .41	*r* = –0.12 (–0.32, 0.13) *P* = .35	T7	r_e = 0.30 (0.08, 0.50) *P* = .02	*r* = 0.50 (0.14, 0.72) *P* = .01	r_e = 0.25 (–0.01, 0.49) *P* = .11	-	-	-	-
	-	-	-	-	T8	r_e = 0.30 (0.05, 0.51) *P* = .02	*r* = 0.41 (0.07, 0.70) *P* = .04	r_e = 0.27 (–0.02, 0.54) *P* = .08	-	-	-	-
Body mass index	L1	*r* = 0.00 (–0.17, 0.18) *P* = .99 n = 81	*r* = 0.11 (–0.66, 0.73) *P* = .67	*r* = –0.01 (–0.21, 0.19) *P* = .92	T5	r_e = 0.17 (–0.07, 0.41) *P* = .16	*r* = –0.20 (–0.63, 0.31) *P* = .34	*r* = 0.18 (–0.06, 0.42) *P* = .21	L3	*r* = –0.24 (– 0.39, 0.07) *P* < .001	*r* = –0.22 (–0.41, –0.01) *P* = .003	*r* = – 0.22 (–0.49, – 0.08) *P* = .03
	L3	*r* = –0.08 (–0.26, 0.09) *P* = .48 n = 81	*r* = 0.08 (–0.62, 0.71) *P* = .74	*r* = –0.11 (–0.29, 0.08) *P* = .41	T6	r_e = 0.25 (0.00, 0.48) *P* = .04	*r* = 0.16 (–0.34, 0.63) *P* = .46	r = 0.34 (0.05, 0.58) *P* = .02	-	-	-	-

	L5	r = –0.25 (–0.41, –0.07) P = .03 n = 81	r = –0.11 (–0.70, 0.77) P = .64	r = –0.27 (–0.45, –0.08) P = .03	T7	r_e = 0.08 (–0.14, 0.30) P = .51	r = 0.19 (–0.28, 0.60) P = .36	r = 0.03 (–0.25, 0.28) P = .83	-	-	-	-
	-	-	-	-	T8	r_e = 0.16 (–0.10, 0.39) P = .19	r = 0.47 (0.17, 0.68) P = .02	r = 0.10 (–0.19, 0.42) P =.49	-	-	-	-
Waist circumference	L1	r = 0.01 (–0.18, 0.21) P = .93 n = 81	r = 0.21 (–0.49, 0.67) P = .39	r = –0.03 (–0.23, 0.19) P = .82	T5	-	-	-	L3	-	-	-
	L3	r = –0.02 (–0.18, 0.16) P = .86 n = 81	r = 0.20 (–0.36, 0.66) P = .42	r = –0.07 (–0.26, 0.13) P = .61	T6	-	-	-	-	-	-	-
	L5	r = –0.15 (–0.32, 0.05) P = .19 n = 81	r = 0.13 (–0.41, 0.72) P = .61	r = –0.2 (–0.38, 0.01) P = .12	T7	-	-	-	-	-	-	-
	-	-	-	-	T8	-	-	-	-	-	-	-
Waist postero-anterior diameter	L1	r = 0.05 (–0.19, 0.27) P = .66 n = 81	r = 0.27 (–0.24, 0.68) P = .27	r = –0.01 (–0.30, 0.24) P = .92	T5	-	-	-	L3	-	-	-
	L3	r = –0.03 (–0.27, 0.19) P = .81 n = 81	r = 0.15 (–0.34, 0.60) P = .54	r = –0.08 (–0.34, 0.19) P = .55	T6	-	-	-	-	-	-	-
	L5	r = –0.12 (–0.34, 0.13) P = .30 n = 81	r = 0.18 (–0.35, 0.72) P = .47	r = –0.19 (–0.43, 0.09) P = .13	T7	-	-	-	-	-	-	-
	-	-	-	-	T8	-	-	-	-	-	-	-
Waist-to-height ratio	L1	r = –0.07 (–0.25, 0.11) P = .56 n = 81	r = 0.08 (–0.50, 0.66) P = .75	r = –0.11 (–0.31, 0.09) P = .41	T5	-	-	-	L3	-	-	-
	L3	r = –0.13 (–0.29, 0.04) P = .24 n = 81	r = 0.04 (–0.50, 0.62) P = .87	r = –0.18 (–0.36, 0.01) P = .16	T6	-	-	-	-	-	-	-
	L5	r = –0.26 (–0.41, –0.06) P = .02 n = 81	r = –0.08 (–0.61, 0.68) P = .76	r = –.31 (–0.48, –0.09) P = .02	T7	-	-	-	-	-	-	-
	-	-	-	-	T8	-	-	-	-	-	-	-

LBP, low back pain.

[a] A significant difference implies lower spinal stiffness in women compared with men.

difference remains unknown, it might explain why some studies[14,16,17] did not report significantly lower spinal stiffness in women because only asymptomatic or healthy participants were included.

Theoretically, age could influence spinal stiffness through changes in body composition over the years. Until the age of 50, a decrease in fat-free mass and an increase in fat mass and abdominal fat can be observed. However, the magnitude of these changes depends on the individual's BMI.[31] Further, age-related spinal degenerative changes may affect spinal stiffness. This complex interaction between BMI, changes in fat composition, spinal degeneration, and age may explain the lack of significant correlations between spinal stiffness and age in the current study as well as in others.[9,11,12,14,17]

The current study also highlights the influence of testing protocol and testing device on spinal stiffness measurements. Spinal stiffness values are known to be affected by parameters such as the applied load, rate of force application (or measurement velocity), measurement angulation, indenter size, and respiration cycle.[5] Participants were instructed to hold their breath at the end of normal exhalation during measurement in the 3 included studies; however, the load, velocity, indenter size, and padding varied across studies. While the data set A device, called VerteTrack,[19] assessed spinal stiffness based on a brief posteroanterior force component applied to the spinous process region, both the data set B and C devices applied a gradual posteroanterior load over the targeted spinous process over a few seconds. Comparisons between spinal stiffness values obtained using both types of devices should be conducted in the future.

Considering the relatively new use of instrumented stiffness measures and the potential value of their measures, a great amount of investigative work remains in this area. Although the utilization of the same or similar device among different institutions is a challenge, future studies should adopt this approach. A common device and protocol across studies and institutions would lead to the development of normative values and ultimately assist clinicians in their evaluation and management of patients with spinal pain. Future studies may also consider normalizing spinal stiffness values (eg, by weight, BMI, or trunk fat caliper measures) to remove or mitigate the effects of some of these factors.

Limitations

Given that this was a secondary analysis of 3 data sets, data collection protocols were unique to each data set, thereby introducing some heterogeneity. It was, however, our purpose to study the results of varying methodology, and this allowed us to identify the correlations between spinal stiffness and individual characteristics that are consistent even with different patient populations, assessment devices, and protocols. We do acknowledge that the development and use of standardized spinal stiffness assessment methodology would allow for the identification of additional individual characteristics that might also be correlated with spinal stiffness. Second, the results of this study are applicable only to the thoracic and lumbar spine. Considering the limited literature regarding correlations between cervical spine stiffness and clinical status, age, and sex,[9,17,32] studies are needed to evaluate correlations with other individual characteristics such as height and weight for comparison with the thoracic and lumbar spine. Finally, we would be remiss not to acknowledge that the small sample sizes of the included data sets may have limited the statistical power of our analysis. Although our study is the largest of its type, we acknowledge the possibility of small samples leading to type 1 error. Notwithstanding, our approach was a narrative synthesis of 3 data sets and, by its nature, attempts to account for single inconsistencies, such as false positives. Given this field of research is currently vulnerable to issues surrounding small samples, we suggest that future in vivo spinal stiffness experiments ensure that a priori sample size requirements have been satisfied.

Clinical Implications

On the basis of the results of the current study, clinicians should be aware that several variables may influence their perception during manual spinal stiffness assessment. Weight, height, BMI, sex, waist circumference, and waist-to-height ratio were all significantly correlated with spinal stiffness in all or some of the included data sets. Furthermore, some variables such as BMI seem to affect thoracic and lumbar spinal stiffness differently. Consequently, clinicians should limit comparison between patients and between spinal levels of distinct spinal regions. Our data support the recommendation that the choice of vertebra to receive a treatment should be based not only on clinical perception during manual spinal stiffness assessment, but also on patient pain during assessment, patient complaint localization, posture, and regional movement.[4]

Conclusion

Three data sets, derived from a total of 5 studies conducted in 3 institutions, were analyzed to describe the main individual characteristics associated with spinal stiffness. The 3 data sets included different testing protocols and testing devices that yielded different spinal stiffness values. Despite these differences, height and BMI were significantly correlated with spinal stiffness, and lower spinal stiffness was observed in women in at least 2 data sets, making these variables of future interest. As such, these variables should be reported in future studies

evaluating spinal stiffness. Moreover, a standardized testing device and protocol, including normalization, should be prioritized in future studies conducted at different research sites.

Acknowledgments

For data set A, the authors thank Aron Downie and Benjamin Brown for their contribution to the project conception and management and the research assistants for their role in data collection. For data set B, the authors thank François Nougarou, PhD, for his assistance in data analysis.

Funding Sources and Conflicts of Interest

For data set A, the Department of Chiropractic, Faculty of Science and Engineering at Macquarie University, provided financial support for the VerteTrack infrastructure and for a Visiting Professor collaboration associated with the VerteTrack infrastructure. For data set B, Isabelle Pagé was supported by the Canadian Institute for Health Research (CIHR) and a Fonds de Recherche du Québec-Santé (FRQS) scholarship for health professionals. For data set C, Arnold Wong was supported by the Alberta Innovates-Health Solutions Graduate Studentship and the Andrew Stewart Memorial Graduate Prize. Greg Kawchuk was supported by the Canada Research Chair Program. Drs. Kawchuk, Wong, and Swain declare that the devices used to collect data at the Polytechnic University of Hong Kong and Macquarie University were fabricated by one of the authors (Kawchuk, patent holder) on a cost-recovery basis to be used only in research trials approved by their own institutions—they are not clinical devices.

Contributorship Information

Concept development (provided idea for the research): I.P., M.S., A.W., A.B., D.D.C., M.D., M.F., G.K.
Design (planned the methods to generate the results): I.P., M.S., A.W., A.B., D.D.C., M.F., G.K.
Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): M.D., G.K.
Data collection/processing (responsible for experiments, patient management, organization, or reporting data): I.P., M.S., A.W., M.D., G.K.
Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): I.P., M.S., A.W.
Literature search (performed the literature search): I.P., M.S., A.W.
Writing (responsible for writing a substantive part of the manuscript): I.P., M.S., A.W., A.B., D.D.C., M.F.
Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): M.D., G.K.

Practical Applications

- Instrumented spinal stiffness assessment evaluates spine biomechanical properties.
- Spinal stiffness was lower in women than in men.
- Spinal stiffness was positively correlated with height, but its relationship with weight varied.
- Body mass index was associated with spinal stiffness.
- Physiological measurement of body weight distribution may affect spinal stiffness.

References

1. Vos T, Flaxman AD, Naghavi M, et al. Years lived with disability (YLDs) for 1160 sequelae of 289 diseases and injuries 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet.* 2012;380(9859):2163-2196.
2. Ferrari R, Russell AS. Regional musculoskeletal conditions: neck pain. *Best Pract Res Clin Rheumatol.* 2003;17(1):57-70.
3. Koes BW, Tulder M, Lin CW, Macedo LG, McAuley J, Maher C. An updated overview of clinical guidelines for the management of non-specific low back pain in primary care. *Eur. Spine J.* 2010;19(12):2075-2094.
4. Triano JJ, Budgell B, Bagnulo A, et al. Review of methods used by chiropractors to determine the site for applying manipulation. *Chiropr Man Therap.* 2013;21(1):36.
5. Snodgrass SJ, Haskins R, Rivett DA. A structured review of spinal stiffness as a kinesiological outcome of manipulation: its measurement and utility in diagnosis, prognosis and treatment decision-making. *J Electromyogr Kinesiol.* 2012;22(5):708-723.
6. Wong AYL, Kawchuk GN. The clinical value of assessing lumbar posteroanterior segmental stiffness: A narrative review of manual and instrumented methods. *PM&R.* 2017;9(8):816-830.
7. Wong AY, Parent EC, Dhillon SS, Prasad N, Kawchuk GN. Do participants with low back pain who respond to spinal manipulative therapy differ biomechanically from nonresponders, untreated controls or asymptomatic controls? *Spine (Phila Pa 1976).* 2015;40(17):1329-1337.
8. Wong AY, Parent EC, Prasad N, Huang C, Chan KM, Kawchuk GN. Does experimental low back pain change posteroanterior lumbar spinal stiffness and trunk muscle activity? A randomized crossover study. *Clin Biomech.* 2016;34:45-52.
9. Snodgrass SJ, Rivett DA, Robertson VJ. Measuring the posteroanterior stiffness of the cervical spine. *Man Ther.* 2008;13(6):520-528.

10. Owens Jr EF, DeVocht JW, Gudavalli MR, Wilder DG, Meeker WC. Comparison of posteroanterior spinal stiffness measures to clinical and demographic findings at baseline in patients enrolled in a clinical study of spinal manipulation for low back pain. *J Manipulative Physiol Ther.* 2007;30(7):493-500.
11. Kumar S. Posteroanterior spinal stiffness at T5, T10, and L3 levels in normal subjects. *PM&R.* 2012;4(5):342-348.
12. Viner A, Lee M, Adams R. Posteroanterior stiffness in the lumbosacral spine. The correlation between adjacent vertebral levels. *Spine (Phila Pa 1976).* 1997;22(23):2724-2729 discussion 9-30.
13. Koppenhaver SL, Hebert JJ, Kawchuk GN, et al. Criterion validity of manual assessment of spinal stiffness. *Man Ther.* 2014;19(6):589-594.
14. Kumar S. Spinal stiffness in asymptomatic subjects. *J Electromyogr Kinesiol.* 2011;21(5):762-766.
15. Wong AY, Kawchuk G, Parent E, Prasad N. Within- and between-day reliability of spinal stiffness measurements obtained using a computer controlled mechanical indenter in individuals with and without low back pain. *Man Ther.* 2013;18(5):395-402.
16. Kumar S, Stoll S. Device, protocol and measurement of regional spinal stiffness. *J Electromyogr Kinesiol.* 2011;21(3):458-465.
17. Snodgrass SJ, Rhodes HR. Cervical spine posteroanterior stiffness differs with neck position. *J Electromyogr Kinesiol.* 2012;22(6):829-834.
18. Chansirinukor W, Lee M, Latimer J. Contribution of ribcage movement to thoracolumbar posteroanterior stiffness. *J Manipulative Physiol Ther.* 2003;26(3):176-813.
19. Brown BT, Blacke A, Carroll V, et al. The comfort and safety of a novel rolling mechanical indentation device for the measurement of lumbar trunk stiffness in young adults. *Chiropr Man Therap.* 2017;25:21.
20. Descarreaux M, Nougarou F, Dugas C. Standardization of spinal manipulation therapy in humans: development of a novel device designed to measure dose-response. *J Manipulative Physiol Ther.* 2013;36(2):78-83.
21. Kawchuk GN, Liddle TR, Fauvel OR, Johnston C. The accuracy of ultrasonic indentation in detecting simulated bone displacement: a comparison of three techniques. *J Manip Physiol Ther.* 2006;29(2):126-133.
22. Merz O, Wolf U, Robert M, Gesing V, Rominger M. Validity of palpation techniques for the identification of the spinous process L5. *Man Ther.* 2013;18(4):333-338.
23. Reichert B. *Palpation Techniques: Surface Anatomy for Physical Therapists*. Stuttgart, Germany: Thieme; 2011.
24. Cooperstein R, Haneline MT, Young MD. The location of the inferior angle of the scapula in relation to the spinal level of prone patients. *J Can Chiropr Assoc.* 2009;53(2):121-128.
25. Hazra A, Gogtay N. Biostatistics Series Module 6: Correlation and linear regression. *Indian J Dermatol.* 2016;61(6):593-601.
26. Pagé I, Nougarou F, Lardon A, Descarreaux M. Changes in spinal stiffness with chronic thoracic pain: Correlation with pain and muscle activity. *PLOS ONE.* 2018;13(12)e0208790.
27. Hattori K, Numata N, Ikoma M, Matsuzaka A, Danielson RR. Sex differences in the distribution of subcutaneous and internal fat. *Hum Biol.* 1991;63(1):53-63.
28. Tizabi A, Mahdavinejad R, Azizi A, Jafarnejadgero T, Sanjari M. Correlation between height, weight, BMI with standing thoracic and lumbar curvature in growth ages. *World J Sport Sci.* 2012;7(1):54-56.
29. Awad MA, Allah A. Relationship between thoracic kyphosis and trunk length in adolescence females. *J Am Sci.* 2012;8(2):580-583.
30. Salamon N. Height of lumbar disc and vertebral body: What is the relation with body mass index, subcutaneous fat thickness, body weight, length and age? European Congress of Radiology, Lecture 1828. European Society of Radiology; 2017. Available at: https://ecronline.myesr.org/ecr2017/index.php?p=recorddetail&rid=7427b349-1ede-4187-a4a2-efa71f3bdb02&t=browsesessions. Accessed January 18, 2019.
31. Boneva-Asiova Z, Boyanov M. Age-related changes of body composition and abdominal adipose tissue assessed by bioelectrical impedance analysis and computed tomography. *Endocrinol Nutr.* 2011;58(9):472-477.
32. Ingram LA, Snodgrass SJ, Rivett DA. Comparison of cervical spine stiffness in individuals with chronic nonspecific neck pain and asymptomatic individuals. *J Orthop Sports Phys Ther.* 2015;45(3):162-169.