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Alterations in trunk bending stiffness following changes in stability and equilibrium demands of a load holding task

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ABSTRACT

The contribution of the trunk neuromuscular system (TNS) to spine stability has been shown in earlier studies by characterizing changes in antagonistic activity of trunk muscles following alterations in stability demands of a task. Whether and/or how much such changes in the response of TNS to alteration in stability demand of the task alter spinal stiffness remains unclear. To address this research gap, a repeated measure study was conducted on twenty gender-balanced asymptomatic individuals to evaluate changes in trunk bending stiffness throughout the lumbar spine's range of flexion following alterations in both stability and equilibrium demands of a load holding task. Trunk bending stiffness was determined using trunk stiffness tests in upright posture on a rigid metal frame under different equilibrium and stability demands on the lower back. Increasing the stability demand by increasing the height of lifted load ~30 cm only increased trunk bending stiffness (~39%) over the lower range of lumbar flexion and under the low equilibrium demand condition. Similarly, increasing the equilibrium demand of the task by increasing the weight of lifted load by 3.5 kg only increased trunk bending stiffness (55%) over the low range of lumbar flexion and under the low stability demand condition. Our results suggest a non-linear relationship between changes in stability and equilibrium demands of a task and the contribution of TNS to trunk bending stiffness. Specifically, alterations in TNS response to changes in stability and equilibrium demand of a given task will increase stiffness of the trunk only if the background stiffness is low.

1. Introduction

Equilibrium and stability of the human spine during daily activities are primarily provided by the trunk neuromuscular system (TNS). While the contribution of TNS to spine equilibrium is directly reflected in an individual's ability to perform an activity (e.g., holding a given trunk posture or moving the trunk in the space as desired), its contribution to spine stability is less clear. Granata and Orishimo (2001) demonstrated the contribution of TNS to spine stability by characterizing changes in antagonistic activity of trunk muscles following alterations in stability demands of a load holding task. Specifically, subjects were instructed to hold a load (4.5 or 9.0 kg) between two vertical guide-bars at different heights, so that the equilibrium demand of the task on the lower back was nearly unchanged given the constant horizontal distance between the load and the lower back, whereas the stability demand of the task was altered by changing the load height (Granata and Orishimo, 2001). Although higher levels of antagonistic muscle activity were found with increasing stability demands, it remained unclear whether and/or how the observed changes in the response of TNS altered spinal stability.

Spinal stability, in a biomechanical sense, is defined as the capacity of the system that provides spinal equilibrium to sustain the equilibrium in the presence of mechanical perturbations. Therefore, spinal stability can partially be assessed through measures of trunk bending stiffness. Increased activity of trunk muscles in recumbent posture has been shown to increase trunk bending stiffness throughout the lumbar spine's range of flexion (Beach et al., 2005; Brown and McGill, 2008, 2010; Lee and McGill, 2015). Similarly, trunk bending stiffness in neutral standing posture was found to increase with increases in activity of trunk muscles (Cholewicki et al., 2000; Gardner-Morse and Stokes, 2001; Stokes and Gardner-Morse, 2003). The main limitation of these

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earlier studies in the assessment of TNS contribution to spinal stability is that in all cases the increase in the activity of trunk muscles was achieved through either changes in the equilibrium requirements of the task (e.g., pre-activation efforts) or intentionally recruiting trunk flexor muscles while maintaining an upright posture (Brown and McGill, 2010; Lee et al., 2006). Therefore, it remains unclear how alterations in TNS following changes in stability requirement of a task, as reported by Granata and Orishimo (2001), affect trunk bending stiffness and spinal stability.

We have developed a new experimental device that enables assessment of trunk bending stiffness in an upright posture throughout the lumbar spine's range of flexion. The objective of this study was set to evaluate changes in trunk bending stiffness throughout the range of flexion following alterations in both stability and equilibrium demands of a load holding task. It was hypothesized that with increasing each of the stability and equilibrium demands of the task, trunk bending stiffness would increase. Considering our recent finding on the effects of gender and lumbar flexion angle on trunk bending stiffness (Shojaei et al., 2016), we further hypothesized that increases in trunk bending stiffness with increases in stability and equilibrium demands will be affected by gender differences and by the passive contribution of trunk tissues to spine equilibrium (i.e., increased contribution under larger lumbar flexion angles). To test our hypotheses, a repeated measure study design similar to that of Granata and Orishimo (2001) was used wherein changes in stability and equilibrium demands of the task were achieved by changing, respectively, the weight and height of the lifted load.

2. Methods

2.1. Participants

Twenty gender-balanced asymptomatic individuals between 18 and 30 years old were recruited from the University of Kentucky's student population. Exclusion criteria were previous history of back pain, evidence of neuromuscular disorders, history of working in physically demanding occupations, involvement in excessive levels of physical activity that might significantly impact the neuromuscular behavior, and a body mass index (BMI) outside the 20–30 kg/m^2 interval. Prior to data collection, all participants completed an informed consent procedure approved by the University of Kentucky Institutional Review Board. The mean (SD) values of stature, body mass, and BMI were respectively 178.0 cm (6.2 cm), 78.9 kg (12.0 kg), and 24.8 (3.5) for males and 164.7 cm (5.1 cm), 67.1 kg (7.0 kg), and 24.7 (3.8) for females.

2.2. Experimental procedures

Each participant completed one experimental session comprising of six trunk stiffness tests in upright posture under different equilibrium and stability demands. Prior to these trunk stiffness tests, each participant conducted a trunk bending–return test, to obtain his/her lumbar spine's range of flexion (Fig. 1). For the trunk bending–return test, participants were instructed to bend their trunk forward from an upright posture to their maximum comfortable bending posture and then to return to their original upright posture. Participants were instructed to repeat the trunk forward bending and backward return three times with a self-selected slow pace. Wireless Inertial Measurement Units (IMUs; Xsens Technologies, Enschede, Netherlands) superficial to the T10 vertebral process and the sacrum (S1) (Fig. 1) were used to measure rotations of the thorax and pelvis as rigid bodies.

Trunk stiffness tests were conducted on a rigid metal frame (Fig. 2), wherein the participant's pelvis was constrained using straps and the upper body was kept upright throughout the experiment using a harness-connecting rigid rod assembly. The stiffness tests were conducted within this frame by rotating the participant's legs (and pelvis as it was constrained and isolated from the upper body) around his/her lower back using an actuated platform. The height of platform was adjusted for each participant such that the platform's axis of rotation coincided with ~ the S1 spinal level (Fig. 2). Since the lower extremities and the pelvis of participants were constrained to the platform and the thorax was fixed in space, it was assumed that the amount of lumbar flexion was the same as the amount of rotation of the platform. The test started with the participant in standing posture, followed by rotation of the legs and pelvis at a constant angular velocity of ~3 deg/s (dictated by the platform's actuator), to achieve a lumbar flexion equal to 70% of the lumbar range of flexion, and then returning them back into the initial standing posture on the frame. The selection of a sub-maximal (i.e., 70%) lumbar flexion for these tests was

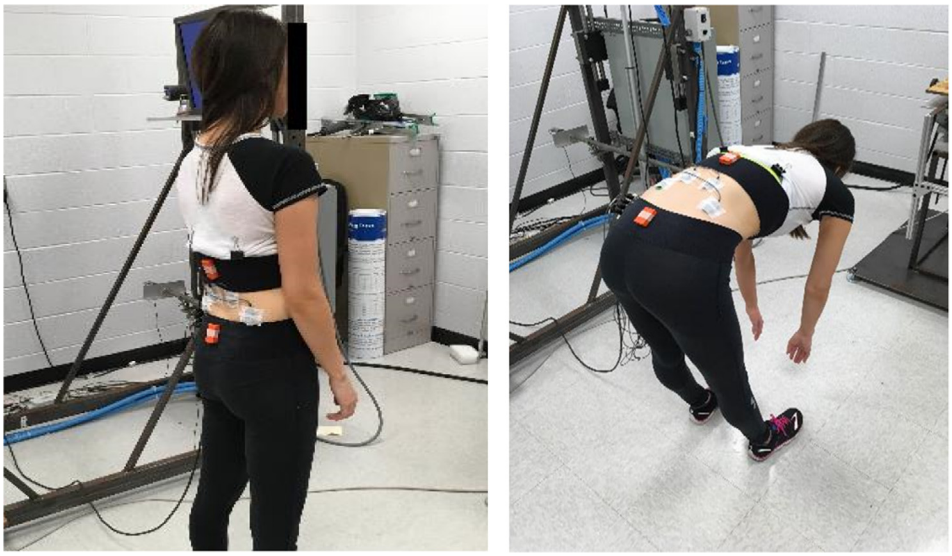

Fig. 1. Wireless Inertial Measurement Units superficial to the T10 vertebral process and the sacrum (S1) as well as surface sensors for collecting electromyography activity of selected back and abdominal muscles (left). The maximum flexed posture during the trunk bending–return test to obtain lower back range of flexion (right).

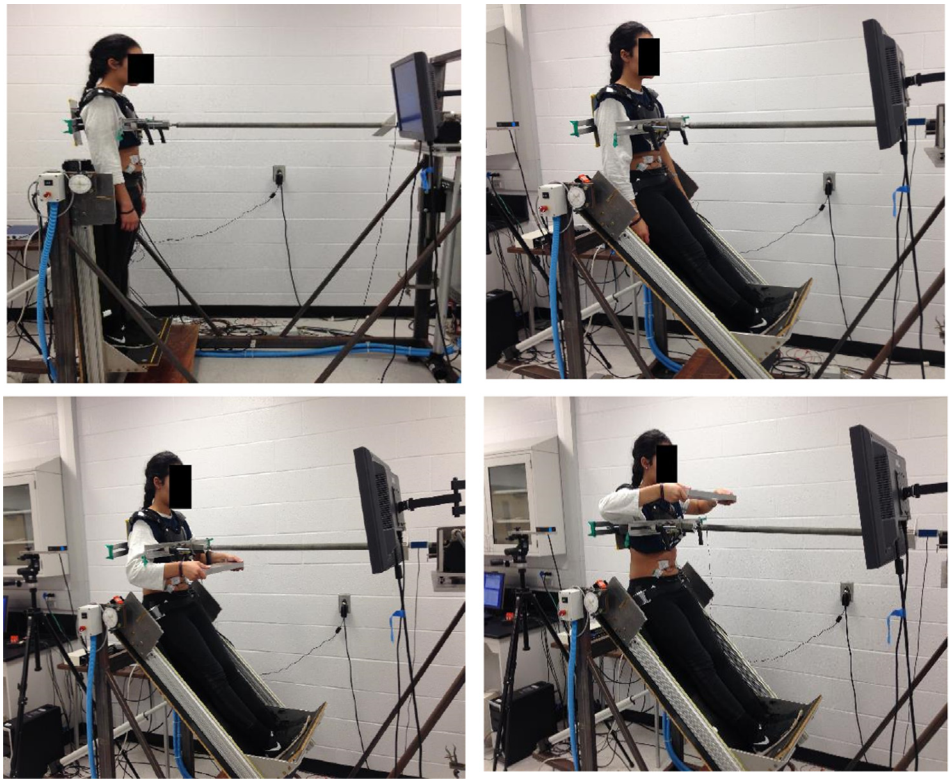

Fig. 2. Experimental setup for the trunk stiffness test in an upright posture (top left). Six trunk stiffness tests were performed including two tests with no load in hands (top right) and four tests with loads (3.5 and 7 kg) in hands held at a fixed horizontal distance from the lower back either below (bottom left) or above (bottom right) the connecting rod. The load of 3.5 kg weight is shown in the figures.

merely done for safety. During these experiments, the rotation of platform was visually controlled using a protractor attached to the leg platform and was measured at 60 samples/s using a wireless IMU (Fig. 2). An inline load cell on the harness-connecting rod assembly (Interface SM2000, Scottsdale, AZ) was used to measure this kinetic response of the trunk at 3000 sample/s (Fig. 2). In a randomized order, each participant completed two trunk stiffness tests with no load in hands and four trunk stiffness tests with two different loads (3.5 kg and 7 kg) held in hands at a fixed horizontal distance from the lower back either below or above the connecting rod. Differences in load magnitudes (i.e., 3.5 kg and 7 kg) were assumed to impose different equilibrium demands on the spine, whereas differences in load heights (i.e., below and above the connecting rod ~30 cm) were assumed to impose different stability demands (Granata and Orishimo, 2001). For each participant, the horizontal distance of the load from the lower back was determined before the tests as the furthest distance that participant could comfortably hold the heaviest load (i.e., 7 kg) above the rod (i.e., most demanding task) for 45 s. The participants were instructed to keep the load position unchanged throughout the entire test. Electromyography (EMG) of selected back muscles (bilateral erector spinae at the L3 and L5 levels) (Fig. 1) and abdominal muscles (bilateral rectus abdominis, and external oblique) (Fig. 2) was collected using a surface EMG system (Delsys, Natick, MA). The full bandwidth of the surface EMG signal spans up to 500 Hz. The Delsys EMG system has built-in anti-aliasing filters, with upper bandwidths of 500 Hz. EMG data were collected at 3000 sample/s and were band-pass filtered (25–500 Hz), full-wave rectified, and low-pass filtered using a dual-pass fourth-order Butterworth filter with a cut-off frequency of 2.5 Hz (Winter, 2009; De Luca et al., 2010). The raw kinematic and kinetic data were low-pass filtered using a dual-pass fourth-order Butterworth filter with a 6 Hz and a 50 Hz cutoff frequency, respectively (Winter, 2009; Kristianslund et al., 2012).

2.3. Data analysis

The pelvic and thoracic rotations measured from the trunk bending–return tests were used to calculate lumbar flexion as the difference between these rotations. The maximum value of lumbar flexion was regarded to be the lumbar range of flexion and was averaged between three repetitions of the trunk bending–return test.

For the trunk stiffness test, the trunk kinetic responses to lumbar flexion (i.e., caused by rotating the participant's legs), measured by the in-line load cell, were initially converted to the lower back moment (Fig. 3) by multiplying them with the distance between the harness and the axis of rotation (~ the S1 spinal level) of the platform, measured for each subject before the trunk stiffness test. Average trunk bending stiffness, K_b, over each quartile of lumbar flexion, as well as over the first 10% of lumbar flexion was calculated during the flexion phase (Figs. 3 and 4) using the following relationship:

$$K_b = \frac{\Delta M}{\Delta \theta} = \frac{M_E - M_S}{\theta_E - \theta_S}$$

where ΔM and $\Delta\theta$ were respectively the changes in the moment and the lumbar flexion angle, M_E and M_S were the moments at respectively the end and the start points of the lumbar flexion interval, θ_E and θ_S were lumbar flexion angles at the end and the start points of the lumbar flexion interval (Figs. 3 and 4).

Furthermore, for each EMG sensor, the mean value of the processed digital EMG over each of the five flexion intervals, that were

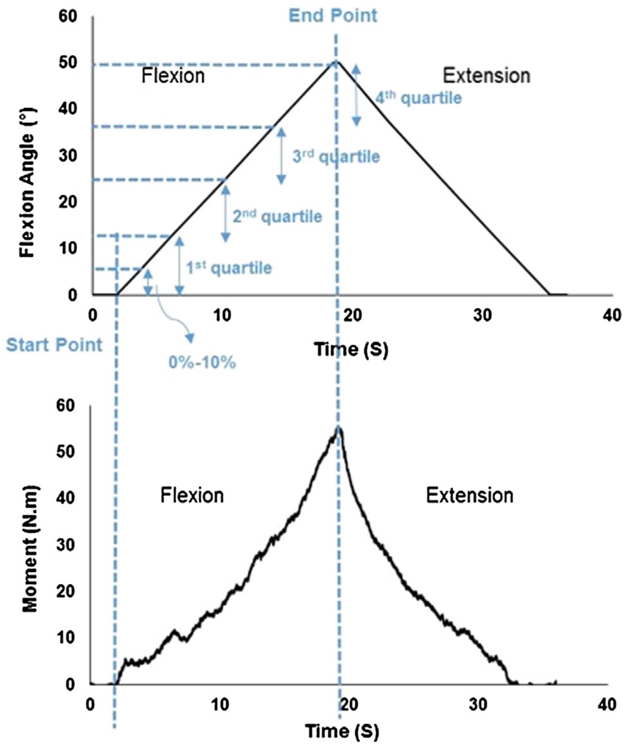

Fig. 3. Samples of lumbar flexion angle and lower back moment used for estimation of the trunk stiffness over five separate intervals in the range of lumbar flexion. The kinematic and kinetic data were synchronized and the start and end points of the flexion were found using kinematic data. The intervals of lumbar flexion over which trunk stiffness was calculated (i.e., 0–10%, 1st quartile, 2nd quartile, 3rd quartile, and 4th quartile) are also shown.

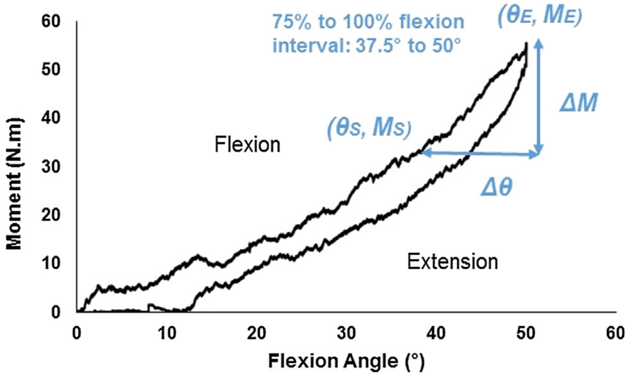

Fig. 4. For each interval the ratio of ΔM over Δθ during the flexion phase of motion was considered as the trunk bending stiffness. ΔM and Δθ for the 4th quartile (i.e., 37.5–50° for a subject with 70% of lumbar flexion equal to 50°) of flexion are shown.

used to estimate trunk stiffness, was calculated. The EMG values from the four back and the four abdominal sensors were then averaged to represent back and abdominal muscle activity in each lumbar flexion interval.

For each loading condition and each lumbar flexion interval, changes in trunk bending stiffness, back and abdominal muscle activities were calculated using the following relationship:

$$\text{Change in variable } (\%) = \frac{x_2 - x_1}{x_1} * 100$$

where x_1 and x_2 were the values of the variable over the same lumbar flexion interval with no load in hands (x_1) and with loading condition (x_2). As such, the changes (%) in the trunk bending stiffness and muscle activities relative to the baseline condition were obtained and used for statistical analysis. Mixed-model analyses of variance (ANOVA) tests were conducted to assess the effects of stability demand (i.e., higher vs. lower height load), equilibrium demand (i.e., heavier vs. lighter load), and interval of flexion (i.e., 0–10%, 1st quartile, 2nd quartile, 3rd quartile, and 4th quartile of lumbar range of flexion) as within-subject factors, and gender (male and female) as between-subject factor on the changes in trunk bending stiffness and trunk muscle activity. Mixed-model ANOVA assumptions were verified, and adjustment for multiple comparisons was set to be Bonferroni's procedure. Data acquisition and analysis were performed using MATLAB (The MathWorks Inc., Natick, MA, USA, version 8.6.0), whereas statistical analyses were performed using SPSS (IBM SMSS Statistics 24, Armonk, NY, USA). Summary values of statistical analyses are reported as means (SD) and in all cases, a p value ≤ 0.05 was considered as statistically significant.

3. Results

Baseline mean values of trunk bending stiffness, back and abdominal muscle activities over each of the studied flexion interval are summarized in Table 1. To further clarify our calculation of changes in dependent variables with loading condition, values of trunk bending stiffness at baseline and loading condition (i.e., the average of bending stiffness for all loading conditions) along with the corresponding changes for each lumbar flexion interval are summarized in Table 2.

3.1. Effects on trunk bending stiffness

There was a three-way interaction involving stability and equilibrium demands as well as interval of lumbar flexion on the changes in the trunk bending stiffness (Table 3). Specifically, for the low equilibrium demand condition (i.e., 3.5 kg load in hands), the simple effects of stability demand were only significant ($F = 2.97$, $p = 0.039$) in the smallest range of lumbar flexion (i.e., 0–10% interval of trunk flexion), such that the higher vs. the lower height load resulted in a larger increase in the trunk bending stiffness (68% vs. 29%) (Fig. 5). Furthermore, for the same interval of flexion and for the low stability demand condition (i.e., condition with load held in lower height), the simple effects of equilibrium demand were significant ($F = 5.68$, $p = 0.003$), such that the increase in trunk bending stiffness was larger for heavier (84%) vs. lighter (29%) loads (Fig. 5). Similarly, for the first quartile of lumbar flexion and for the low stability demand condition, the simple effects of equilibrium demand were significant ($F = 3.17$, $p = 0.031$) such that the increase in trunk bending stiffness was larger for heavier (67%) vs. lighter (27%) loads (Fig. 5). No other main effects on trunk bending stiffness were found (Tables 3 and 4).

3.2. Effects on trunk muscle activity

3.2.1. Back muscles

There were two three-way interactions, involving stability and equilibrium demands as well as interval of lumbar flexion or gender, and one two-way interaction, involving interval of lumbar flexion and gender, on back muscle activity (Table 3). Except for the 0–10% flexion interval, for all other lumbar flexion intervals and under the low equilibrium demand condition, the simple effects of stability demand were significant ($F > 8.68$, $p < 0.009$), where the higher vs. lower height load resulted in a larger increase in back muscle activity (1st quartile: 83% vs. 47%; 2nd quartile: 84% vs. 47%; 3rd quartile: 89% vs. 40%; 4th quartile: 88% vs. 28%) (Fig. 6). Also, for the 0–10% interval, and 1st and 2nd quartiles of

Table 1
Baseline mean (SD) of stiffness (Nm/rad), back and abdominal muscle activity (μV) over different intervals of lumbar flexion.

Baseline measures	0–10%	1st quartile	2nd quartile	3rd quartile	4th quartile
Stiffness (Nm/rad)	50.0 (28.7)	48.4 (30.1)	57.0 (37.8)	54.7 (46.4)	91.8 (40.2)
Back muscle activity (μV)	31.6 (8.0)	30.9 (9.5)	32.7 (10.1)	30.0 (8.6)	31.5 (9.1)
Abdominal muscle activity (μV)	49.5 (14.1)	50.3 (13.0)	48.6 (13.6)	49.2 (13.6)	50.9 (12.1)

Table 2
Mean values of trunk bending stiffness at baseline and loading condition (i.e., the average of bending stiffness for all loading conditions) along with the corresponding changes for each lumbar flexion interval.

Stiffness (Nm/rad)	0–10%	1st quartile	2nd quartile	3rd quartile	4th quartile
Baseline	50.0 (28.7)	48.4 (30.1)	57.0 (37.8)	54.7 (46.4)	91.8 (40.2)
Loading condition	80.1 (35.5)	72.3 (41.3)	62.9 (39.4)	69.9 (49.1)	114.8 (42.5)
Change	60%	49%	10%	28%	25%

Table 3
Summary of statistics results for the effects of stability demand (i.e., higher height load and lower height load), equilibrium demand (i.e., heavier load and lighter load), interval of flexion (i.e., 0–10%, 1st quartile, 2nd quartile, 3rd quartile, and 4th quartile of lumbar range of flexion), and gender (i.e., male and female) on the changes in trunk bending stiffness and trunk back and abdominal muscle activity.

	Trunk bending stiffness		Muscle activity (Back)		Muscle activity (Abdominal)	
	F	*p*	*F*	*p*	*F*	*p*
Stability demand (S)	1.37	0.259	6.65	**0.020**	1.42	0.252
Equilibrium demand (E)	3.45	**0.037**	41.14	**<0.001**	20.13	**<0.001**
Interval of flexion (I)	1.26	0.294	1.90	0.122	3.40	**0.014**
Gender (G)	0.01	0.931	0.29	0.596	0.10	0.762
S × E	7.03	**0.017**	7.40	**0.015**	6.72	**0.020**
S × I	2.42	0.057	3.46	**0.013**	2.89	**0.029**
S × G	0.02	0.882	0.37	0.553	2.48	0.135
E × I	0.54	0.706	26.72	**<0.001**	3.52	**0.012**
E × G	0.19	0.670	2.17	0.160	22.75	**<0.001**
I × G	1.64	0.176	5.09	**0.001**	1.28	0.289
S × E × I	5.72	**0.001**	5.34	**0.001**	1.86	0.128
S × E × G	0.38	0.549	8.35	**0.011**	0.00	0.974
S × I × G	1.86	0.128	1.59	0.187	3.70	**0.013**
E × I × G	1.81	0.138	0.47	0.760	0.52	0.721
S × E × I × G	1.80	0.139	1.21	0.316	2.85	**0.031**

Boldface indicates significant effect.

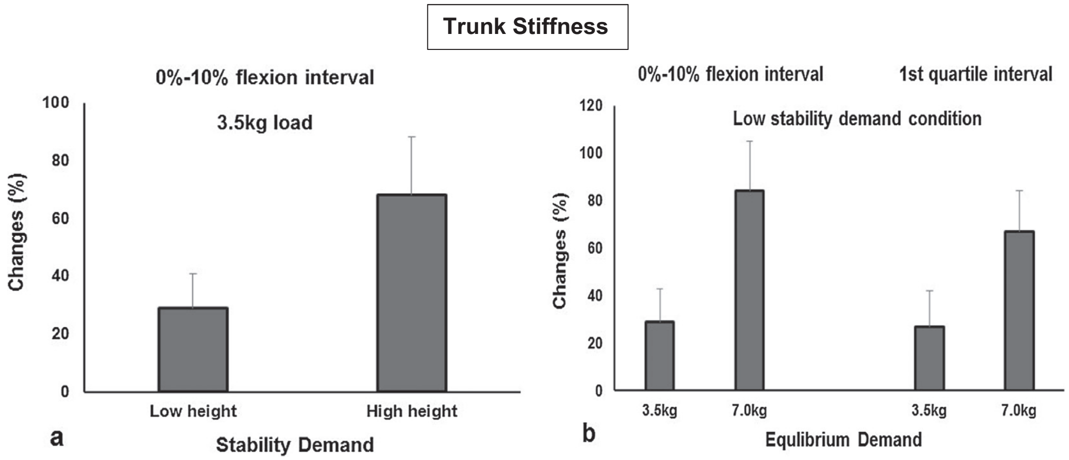

Fig. 5. In flexion intervals wherein changes in trunk bending stiffness with alterations in stability and equilibrium demands of task were significant, they were larger under (1) the higher height vs. lower height load for the low equilibrium demand condition (a) and (2) the heavier load vs. lighter load for the low stability demand condition (b).

lumbar flexion, regardless of stability demand, the simple effects of equilibrium demand were significant (*F > 35.95, p < 0.001*), where the heavier vs. lighter load resulted in a larger increase in back muscle activity (0–10% interval: 142% vs. 75%; 1st quartile: 127% vs. 65%; 2nd quartile: 118% vs. 65%) (Fig. 6). However, for the 3rd and 4th quartiles of lumbar flexion only under the low stability demand condition, the simple effects of equilibrium demand were significant (*F > 15.95, p < 0.001*) where heavier vs. lighter loads resulted in a larger increase in back muscle activity (3rd quartile: 112% vs. 40%; 4th quartile: 89% vs. 28%) (Fig. 6).

The simple effects of stability demand were significant (*F = 18.71, p = 0.002*) only in male participants in the low equilibrium demand condition, where higher vs. lower height load resulted in a larger increase in back muscle activity (94% vs. 37%) (Fig. 6). Also, the simple effects of equilibrium demand were significant ($F = 31.02$, $p < 0.001$), only in male participants under low stability demand condition, where heavier vs. lighter load resulted in a larger increase in back muscle activity (114% vs. 37%) (Fig. 6).

Table 4
Summary of outcome measures including mean (SD) for the effects of stability demand (i.e., higher height load and lower height load), equilibrium demand (i.e., heavier load and lighter load), interval of flexion (i.e., 0–10%, 1st quartile, 2nd quartile, 3rd quartile, and 4th quartile of lumbar range of flexion), and gender (i.e., male and female) on the changes (%) in trunk bending stiffness and trunk back and abdominal muscle activity. L: Low; H: High.

		Stability Demand		Equilibrium Demand		Interval of Flexion					Gender	
		L	H	L	H	0–10%	Q1	Q2	Q3	Q4	Male	Female
Changes in trunk bending stiffness (%)	Mean	25	44	17	52	60	49	10	28	25	35	34
	SD	11	17	10	21	18	22	19	16	16	19	17
Changes in back muscle activity (%)	Mean	79	105	66	118	109	96	92	86	77	86	98
	SD	15	18	17	23	18	14	16	19	15	18	20
Changes in abdominal muscle activity (%)	Mean	17	21	14	24	17	14	18	22	24	21	17
	SD	7	8	6	9	8	6	8	10	9	10	8

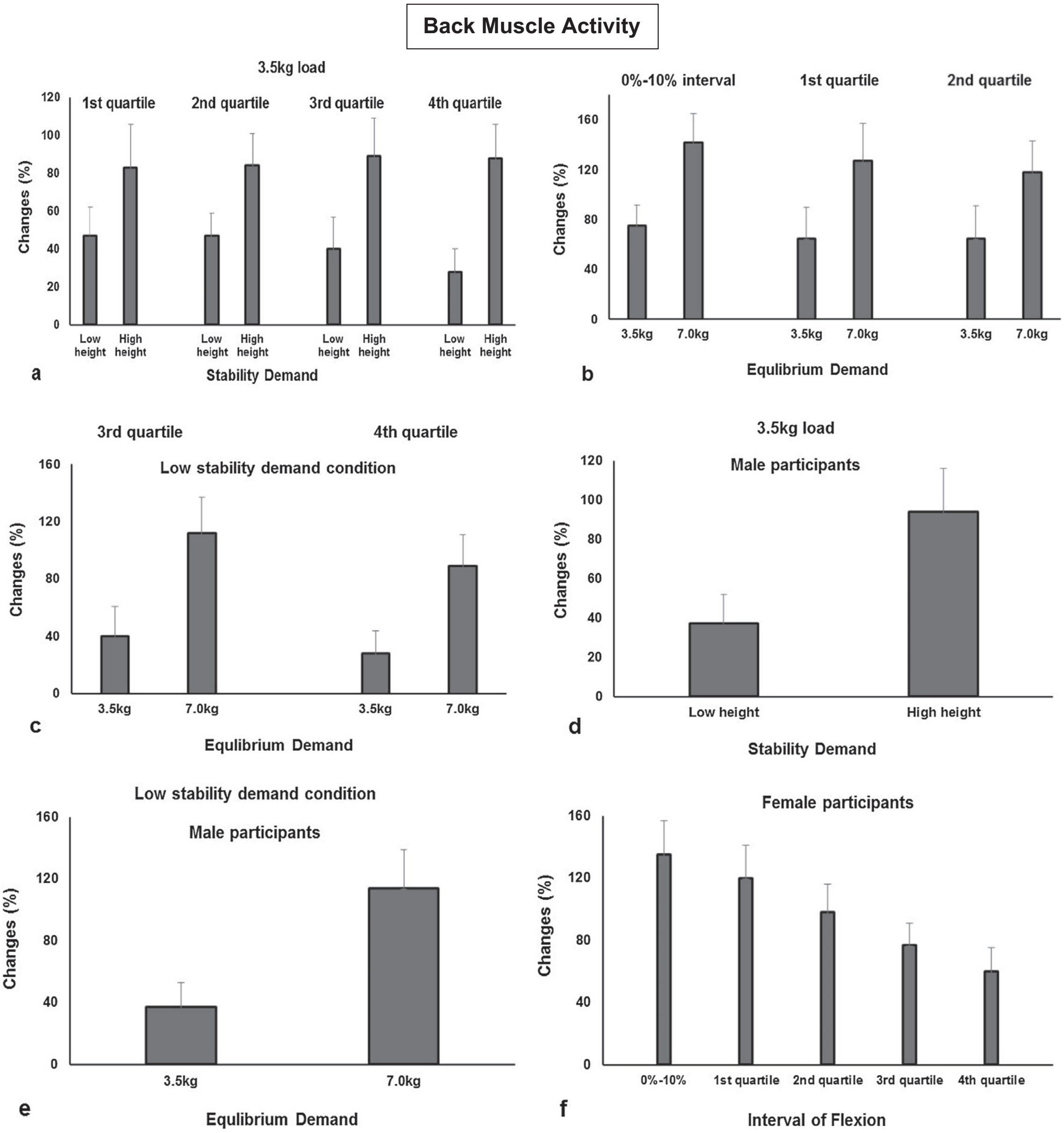

Fig. 6. Under the low equilibrium demand condition, alterations in stability demand caused significant changes in back muscle activity (1) in all quartiles of lumbar flexion (a) and (2) in male participants (d). Similarly, under low stability demand condition, alterations in equilibrium demand changed back muscle activities in male participants (e) as well as in all quartiles of lumbar flexion (b and c). Changes in equilibrium demands under high stability demand conditions also caused significant changes in back.

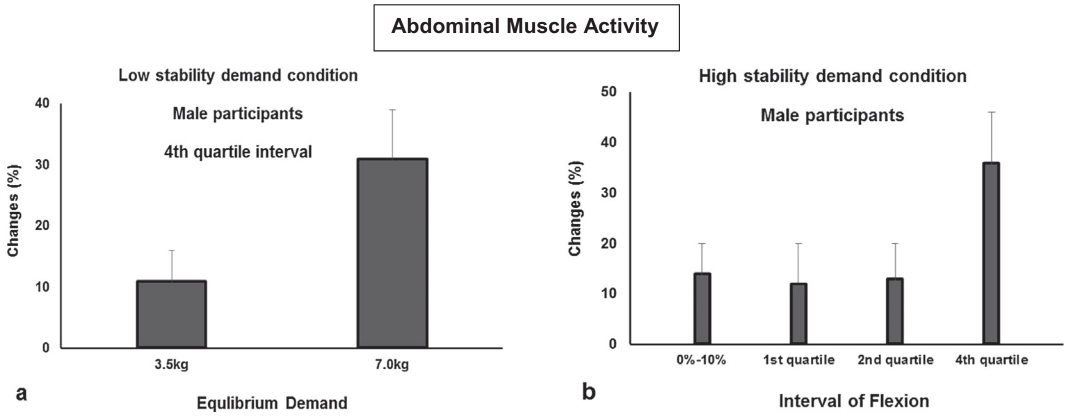

Fig. 7. In male participants, alterations in abdominal muscle activity were larger under heavier vs. lighter load only for the condition involved low stability demand and over the 4th quartile of lumbar flexion (a). Under high stability demand condition of male participants the changes in abdominal muscle activity was larger in the 4th quartile of trunk flexion than the first three intervals (b).

The simple effects of interval of lumbar flexion were significant ($F = 29.83$, $p < 0.001$) only in female participants where, regardless of stability and equilibrium demand conditions, changes in back muscle activity continuously decreased from beginning toward the end-range of lumbar flexion (0–10% interval: 135%; 1st quartile: 120%; 2nd quartile: 98%; 3rd quartile: 77%; 4th quartile: 60%) (Fig. 6).

No other main effects on back muscle activity were found (Tables 3, and 4).

3.2.2. Abdominal muscles

There was a significant four-way interaction effect on the abdominal muscle activity involving all independent variables (Table 3). Specifically, the simple effects of equilibrium demand were significant ($F = 4.98$, $p = 0.048$) only in male participants under the low stability demand condition and in the 4th quartile of trunk flexion, where heavier vs. lighter load resulted in a larger increase in abdominal muscle activity (31% vs. 11%) (Fig. 7). Also, the simple effects of interval of trunk flexion were significant ($F = 5.23$, $p = 0.002$) only in male participants in the high stability demand condition, where the changes in abdominal muscle activity was larger in the 4th quartile of trunk flexion (36%) than the first three intervals (0–10%: 14%; 1st quartile: 12%; 2nd quartile: 13%). No other main effects on abdominal muscle activity were found (Tables 3, and 4).

4. Discussion

The purpose of this study was to evaluate changes in trunk bending stiffness throughout the lumbar spine's range of flexion following alterations in both stability and equilibrium demands of a load holding task. For the increase in stability demand considered in our experiments (i.e., $\sim$30 cm change in load height equal to 10.3 J and 20.6 J change in potential energy for the 3.5 kg and 7.0 kg load, respectively), trunk bending stiffness only increased in the lower range of lumbar flexion (i.e., where passive contribution of tissues is minimal) and under the low equilibrium demand condition (i.e., where muscle activity required for equilibrium was lower). Similarly, for the increase in equilibrium demand considered in our study (i.e., 3.5 kg increase in the lifted load), trunk bending stiffness only increased over the low range of lumbar flexion and under the low stability demand condition. Therefore, our hypothesis on increases in the trunk bending stiffness with increases in equilibrium and stability demands of the task was only partially supported. Furthermore, changes in trunk bending stiffness with alterations in equilibrium and stability demands of the tasks were affected by the passive contribution of trunk tissues, but were not different between males and females. Therefore, our hypotheses regarding the effects of passive tissues contributions and gender were partially confirmed.

When baseline demand was low (i.e., when holding the lighter load at the lower height level around neutral standing posture), increases in either stability or equilibrium demand of the task resulted in increases in trunk bending stiffness. However, when the baseline demand was high, increases in stability or equilibrium demands of the task didn't increase trunk bending stiffness. Therefore, our findings concur with earlier reports on increases in trunk bending stiffness as a result of increases in trunk muscle activity around neutral standing posture (i.e., whether due to increases in equilibrium and stability demands of the task) (Gardner-Morse and Stokes, 2001; Lee et al., 2006; Vazirian et al., 2016). However, as our results show, such a relationship between the equilibrium and stability demands of the task, trunk muscle activity, and trunk bending stiffness is likely a non-linear relationship. Similarly, Cholewicki et al. (2000) reported that increases in equilibrium demand of an extension (flexion) task from 0% to 10% versus from 10% to 20% of body weight were associated with 49% (36%) versus 9% (10%) increases in trunk bending stiffness (Cholewicki et al., 2000). Such a non-linear response to changes in equilibrium demand may stem from the non-linear mechanical behavior of active muscles (Ettema and Huijing, 1994; Joyce et al., 1969; Pousson et al., 1990). Non-linear changes in trunk bending stiffness with changes in stability demand, on the other hand, may be due to differences in TNS response to changes in stability demand. Specifically, we observed changes in muscle activity, particularly back muscles, only with changes in stability demand under low equilibrium demand conditions (Fig. 6a). Differences in TNS response to changes in stability demand may in turn be due to baseline differences in lumbar stiffness. Under high equilibrium demand, the lumbar spine has a relatively high stiffness (Adams et al., 2006; Janevic et al., 1991; Stokes et al., 2002), due to the higher muscle activity, and may not be at risk of instability with the amount of changes in stability demand of the task considered in this study (Bazrgari and Shirazi-Adl, 2007; Cholewicki et al., 1997).

While we observed alteration in back muscle activity with changes in both equilibrium and stability requirements of the task, we did not in general observe any changes in abdominal muscle activity (expect for changes with equilibrium demand over the fourth quartile of lumbar flexion and under low stability demand among males; Fig. 7a). Granata and Orishimo (2001) reported significant effects of the stability demand on abdominal muscle activity, however, their post-hoc analysis indicated that the muscle activity increased only when the change in the load height was greater than 40 cm and the baseline demand was low. Specifically, they observed changes in the abdominal muscle activity when they changed the load height from 20 cm to 60 cm (i.e., equal to 13.2 J to 39.7 J potential energy), whereas they did not observe changes in the abdominal muscle activity when changed the load height from 20 cm to 40 cm (13.2 J to 26.4 J) or from 40 cm to 80 cm (26.4 J to 52.8 J). Therefore, the reason that we did not observe significant changes in abdominal muscle activity with changes in the stability (17–21%) and equilibrium (14–24%) demands of the task might be due to the relatively small changes in the load height (~30 cm) in our study.

We did not observe any gender-related differences in changes in the trunk bending stiffness and muscle activity with changes in equilibrium and stability demand of the task. However, as also reported by Granata and Orishimo (2001), the activity of abdominal muscles was larger (18%) in females vs. males. Granata and Orishimo (2001), however, reported a larger difference between gender than that observed in our study (i.e., 32% vs. 18%), which could be because of heavier loads and larger changes in the height of load in their study (4.5 and 9.0 kg, 80 cm change in load height).

Consistent with our earlier study (Shojaei et al., 2016), we observed a constant level of back and abdominal muscles activities across all intervals of motion for the baseline (i.e., no load) condition. However, we observed a reduction in the changes of back muscle activity with the increase in lumbar flexion among females (Fig. 6f), and an increase in the changes of abdominal muscle activity with increase in lumbar flexion under high stability demand condition among males (Fig. 7b). Both findings suggest changes in trunk muscle recruitment that appear to facilitate (i.e., relaxation of back muscles or activation of abdominal muscles) the applied rotation. One reason for such changes, while considering no changes in trunk bending stiffness with changes in lumbar flexion, could be the increase in passive stiffness of lumbar spine, relative to the no load condition, in the presence of loading. Whether TNS alterations with changes in lumbar flexion are such to provide a margin of spinal stability, hence a constant trunk bending stiffness, remains unclear. The gender-specific responses as well as the role of change in muscle length in such observations also remain unclear and require further investigations.

Although the present study contributes to the current understanding of changes in trunk bending stiffness and muscle activity with alterations in stability and equilibrium demands of the task, it generated some new questions. The results of our study should be interpreted in the light of our study limitations. First, we limited the changes of the weight and height of the load to allow passive flexion and extension of lower back by our testing device. Second, given the viscoelastic nature of lower back tissues, the effects of flexion rate on our measures of trunk bending stiffness should not be overlooked. Third, we only collected EMG activity of superficial muscles while the role of deep muscles in stabilizing the trunk has been recognized to be important. Our estimates of TNS contribution to spine stability only accounted for volitional response of TNS to changes in stability and equilibrium demands of the task. An important aspect of TNS contribution to spinal stability is its contribution through the reflexive feedback (Van Drunen et al., 2013), which was not investigated in this study. Finally, our experimental setup for the trunk stiffness test provides partial support to the trunk through the harness-connecting rigid rod assembly. Such a setup eliminates the likelihood of spinal instability due to large horizontal translation of the trunk and can be expected to have impacted trunk neuromuscular response of our participants to changes in task demand.

In summary, our results suggested a non-linear relationship between changes in stability and equilibrium demands of a task and the volitional contribution of TNS to trunk bending stiffness. Specifically, alterations in TNS response to changes in stability and equilibrium demand of a given task will increase stiffness of the spine only if the background stability condition is low (i.e., lower stiffness level).

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Conflict of interest

The authors have no conflict of interest to declare.

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