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EFFECTS OF GENDER, PRELOAD, AND TRUNK ANGLE ON INTRINSIC TRUNK STIFFNESS

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ABSTRACT

Gender, lifting loads, and flexed trunk postures are three risk factors associated with low back pain. Previous studies have not found gender differences in effective trunk stiffness (intrinsic stiffness plus reflex response) using force perturbations, but these measures may have been confounded by differences in trunk kinematics between males and females. The purpose of this study was to investigate the effects of gender, trunk extensor preload, and trunk flexion angle on intrinsic trunk stiffness using position perturbations, which have the potential to eliminate kinematic differences between research subjects and to separate intrinsic stiffness from reflex responses. A total of 13 males and 12 females were exposed to sudden, small trunk flexion position perturbations with two trunk extension preloads (0 and 30% maximum) and three trunk flexion angles (0, 20, and 40 degrees). Data collected during position perturbations were used along with a two degree of freedom model of the trunk and connecting elements to estimate intrinsic trunk stiffness. Intrinsic stiffness was lower in females compared to males, and increased with increasing preload and trunk flexion angle. Intrinsic stiffness increased

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more substantially among males with increasing preload and trunk angle, and effects of trunk angle were diminished with a preload. A lower intrinsic stiffness and smaller increases with preload and trunk angle, may contribute to the increased rate of occupational LBP and injury among females.

Keywords: Spine; Low back; Neuromuscular control; Posture; Exertion; Male; Female; Biomechanics.

INTRODUCTION

Altered stress and strain distributions within trunk tissues have been suggested as a proximate cause of low back pain (LBP).[1,36] Such distributions are a function of spine mechanics, which involve contributions from passive trunk tissues (i.e., ligaments, intervertebral discs, vertebrae, and passive components of muscle-tendon units) and active trunk neuromuscular control.[26–29] The latter can contribute to trunk mechanical behaviors and spine mechanics via voluntary and reflexive muscle responses to equilibrium and stability requirements. Impaired neuromuscular control could lead to abnormal spine mechanics due to an inappropriate or insufficient response following a spinal disturbance. Numerous studies have assessed the neuromuscular control of the trunk, commonly by characterizing mechanical behavior in response to sudden force perturbations applied to the trunk (or static forces suddenly released from the trunk).[8,14,26,27] Several of these studies have identified differences in neuromuscular control between healthy individuals and those with LBP. For example, following the sudden release of a trunk extension load, individuals with LBP exhibited longer paraspinal reflex latencies,[31–33] greater effective trunk stiffness, and lower effective trunk damping.[14] Use of the word "effective" when describing stiffness and damping indicates that these measures included both intrinsic (due to passive and active stiffness) and reflexive responses to a perturbation.

The effects of several risk factors for LBP on neuromuscular control of the trunk have also been investigated. Gender is one such risk factor in that females experience LBP or injury more than twice as frequently as males in occupational settings that involve lifting.[6,22,23] Females are also more likely to be limited in their activities due to LBP one year following an initial incident.[34] Two additional risk factors for work-related LBP include lifting loads and flexed trunk postures.[19,30,35] More generally, it is theorized that there are particular thresholds of lifting repetition and exertion, beyond which the risk of LBP increases.[19] Previous studies have used force perturbations to investigate how these risk factors affect the mechanical behavior of the trunk. No differences were found between males and females in reflex latency[11] or effective trunk stiffness,[12,26] whereas increasing trunk extensor preload[5,8,12,26] and trunk flexion angle[12] both increased effective trunk stiffness. In the absence of both a trunk extensor preload and a flexed trunk posture, however, females have exhibited shorter paraspinal muscle reflex latencies than males.[25]

While relatively easy to implement, the use of force perturbations to characterize the mechanical behavior of the trunk can potentially introduce confounding effects. For example, force perturbations can result in differences in trunk kinematics across participants due to variations in trunk mass. This is problematic because reflexes are dependent upon muscle lengthening velocity.[16,18,27] To address this problem, some investigators have adjusted the applied load to be a fixed percentage of participants' trunk and head masses[20] while others have normalized the applied impulse force by trunk flexion velocity[25] prior to characterizing trunk mechanical behaviors. These strategies do not ensure identical trunk kinematics, however, since other characteristics of the spine are involved in the response. Another limitation of using force perturbations is the inability to separate intrinsic and reflex responses, since force perturbations and the resulting trunk response typically occur over longer durations than paraspinal muscle reflex latencies.[10,15] This is a clear limitation if intrinsic stiffness and reflexes respond differently to various risk factors.

An approach to characterize the mechanical behavior of the trunk using sudden *position* perturbations has recently been developed.[2,13] With this approach, a motor is controlled to move the trunk a prescribed distance in a prescribed duration. Compared to force perturbations, the use of position perturbations has at least two benefits. First, it has the potential to eliminate variations in trunk kinematics across participants that can confound both stiffness and reflex measurements. Second, trunk movement can be completed prior to typical paraspinal muscle reflex latencies, allowing the intrinsic response to be separated from the reflex response. Based upon these benefits and the aforementioned risk factors for LBP, the purpose of this study was to utilize position perturbations to investigate the effects of gender, preload (lifting load), and trunk angle (flexion) on intrinsic trunk stiffness. It was hypothesized that intrinsic trunk stiffness would be higher in males and increase with both increasing preload and trunk angle.

METHODS

Participants included 13 male (mass mean $\pm$ SD: 73.8 ± 6.32 kg; height: 1.79 ± 0.06 m; age: 21.1 ± 1.12 yr) and 12 female (mass: 59.2 ± 4.9 kg; height: 1.69 ± 0.04 m; age: 24.0 ± 6.5 yr) young adults recruited from the university community, none of whom had a reported history of LBP. This study was approved by the Virginia Tech Institutional Review Board, and written consent was obtained from all participants.

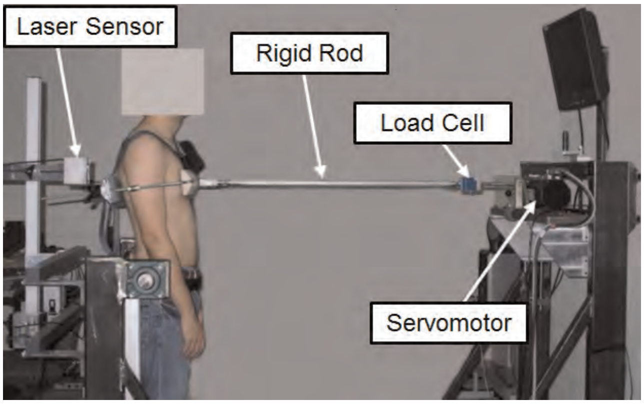

Fig. 1 Experimental set up (adapted from Bazrgari *et al.*[2]).

Intrinsic trunk stiffness was determined using sudden trunk flexion position perturbations.[2,13] Participants were restrained from the pelvis down in a rigid metal frame (Fig. 1) and attached to a servomotor (Kollmorgen AKM53K, Radford, VA, USA) at the T_8 level of the spine via a rigid harness/rod connection. The motor height and frame were adjustable so that the rod connection was horizontal and the trunk could rotate about the L_5S_1 joint. During each 40-second trial, the motor applied a series of 12 anterior and 12 posterior position perturbations, each moving the rod connection 10 mm with a peak velocity of 207.5 mm/s. Perturbations were completed within ~ 40 ms, which is shorter than typical erector spinae delays.[10,15] Pseudorandom delays between each perturbation minimized participant anticipation. Participants were exposed to six experimental conditions including all combinations of two trunk extension preloads (0% and 30% of maximum voluntary exertion, MVE) and three trunk flexion angles (0, 20, and 40 degrees of flexion from the upright posture). One trial was completed at each of these experimental conditions, in random order. Prior to perturbation trials, trunk extension strength was measured during two isometric MVEs with the participant at a 0 degree trunk angle using a load cell (Interface SM2000, Scottsdale, AZ, USA) in line with the rod connecting the motor to the harness. During relevant trials, the preload was maintained at 30% MVE by using a real-time display of RMS erector spinae muscle activity (~3 cm from the midline at the L_3 level). Trunk angle was adjusted by rotating the legs forward/upward, instead of bending over at the trunk, thereby removing any trunk flexor torque due to gravity. To induce trunk flexion rather than hip flexion when rotating the legs forward, participants were strapped to the rotating part of the apparatus across the left and right anterior superior iliac spines of the pelvis. Participants were instructed to maintain the prescribed preload and otherwise not attempt to resist or intervene with the perturbations. Adequate rest was provided between the two MVEs and each perturbation trial.

During each trial, motor displacement (i.e. applied perturbation) was sampled at 1000 Hz using a high accuracy encoder on the shaft of the motor. Trunk displacement (i.e. kinematic response) was sampled at 1000 Hz with a high accuracy CCD laser displacement sensor (Keyence LK-G 150, Osaka, Japan) focused on the midline of the dorsal spine just above the rod height. To account for the vertical offset between the laser sensor and the connecting rod, laser measurements were multiplied by the ratio of these heights from L_5S_1. Load cell force in the rod was sampled at 1000 Hz. All data were low-pass filtered at 10 Hz (7th-order, zero-phase-lag Butterworth filter). Representative displacements and force data are shown in Fig. 2.

Trunk properties were estimated using a two degree-of-freedom model of the trunk and harness/rod connection, in the same manner as previous work.[2,3,13] Briefly, inputs to the model were the displacements collected from the motor encoder and laser sensor along with their numerically calculated 1st and 2nd derivatives. The

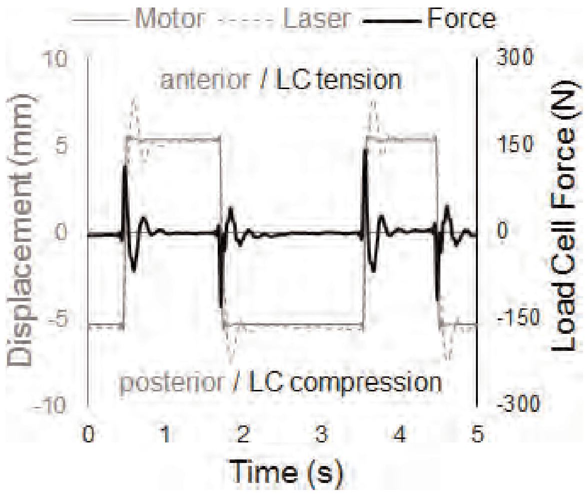

Fig. 2 Representative data from the motor encoder, laser sensor, and load cell (LC). Analyses were limited to the trunk flexion perturbations (i.e. anterior displacements and tension forces).

output was an estimated force response. Model parameters (stiffness, damping, and mass) were determined for each degree of freedom using a curve fit routine in MATLAB™ (MathWorks, Natick, MA, USA) that minimized the total squared difference between estimated and measured forces for each anterior perturbation. Initial efforts failed to consistently differentiate stiffness and damping, possibly due to the short time interval over which our analysis was conducted. As such, trunk damping was set to zero, similar to previous reports.[3,8,13] Therefore, changes in trunk mechanical behavior in this study are represented by changes in stiffness and apparent mass. The model was fit separately to the 12 perturbations in each trial when the trunk was pulled anteriorly (i.e. when a tensile force in the load cell was recorded). Intrinsic stiffness was obtained as the trunk parameter derived from the best model fit within each trial. Forces predicted by the model were highly correlated with experimentally measured forces ($r = 0.996$), suggesting adequate representation of the system dynamics.

Separate three-way, mixed-factor analyses of variance (ANOVAs) were used to investigate the effects of gender, preload, and trunk angle, on intrinsic trunk stiffness and measured peak trunk velocity (from the laser). Peak trunk velocity was included in the analysis to explore the control of trunk kinematics. Contrasts and simple effects analyses were used to investigate any significant interactions. MVE forces (measured from load cell) and moments (product of force and distance from L_5S_1 to T_8 spinous processes) were compared between males and females using a Student's *t*-test. Statistical analyses were conducted using JMP 8 (SAS Software, Cary, NC, USA) and a significance level of $p \leq 0.05$.

RESULTS

During MVEs of isometric trunk extension, males produced 74% greater force (mean ± SD: 604.31 ± 243.62 N) than females (347.38 ± 125.51 N; $p = 0.003$). These forces corresponded to 86% greater maximum trunk extension moments (194.88 ± 90.24 Nm) among males compared to females (104.59 ± 37.57 Nm; $p = 0.004$). Thus, the 30% MVE preload condition corresponded to L_5S_1 extension moments averaging 58 Nm for males and 31 Nm for females.

Intrinsic trunk stiffness exhibited significant main effects of gender ($p < 0.001$), preload ($p < 0.001$), and trunk angle ($p < 0.001$), as well as two-way interactions of gender × preload ($p < 0.001$) and preload × trunk angle ($p = 0.023$). The gender × trunk angle interaction approached significance ($p = 0.069$), and the three-way interaction was not significant ($p = 0.890$). Three *general* observations (Fig. 3) were supported from statistical contrasts. First, females exhibited less intrinsic stiffness than males within each combination of trunk angle and preload (ranging from $p = 0.060$ to $p < 0.001$). This includes the baseline condition of a 0 degree trunk angle and 0% MVE preload, where females exhibited 32% less intrinsic stiffness (4.26 ± 1.91 N/mm) than males (6.29 ± 2.84 N/mm; $p = 0.060$). Second, increasing preload from 0 to 30% MVE increased intrinsic stiffness within each gender and trunk angle combination ($p < 0.001$). Third, increasing trunk angle from 0 to 40 degrees increased intrinsic stiffness within each gender and preload combination ($p < 0.010$).

While the effects of gender, preload, and trunk angle appeared to be fairly consistent across experimental conditions (Fig. 3), simple effects analyses revealed significant two-way interactions ($p < 0.001$) between each pair of independent variables at each level of the third independent variable. First, the gender × preload

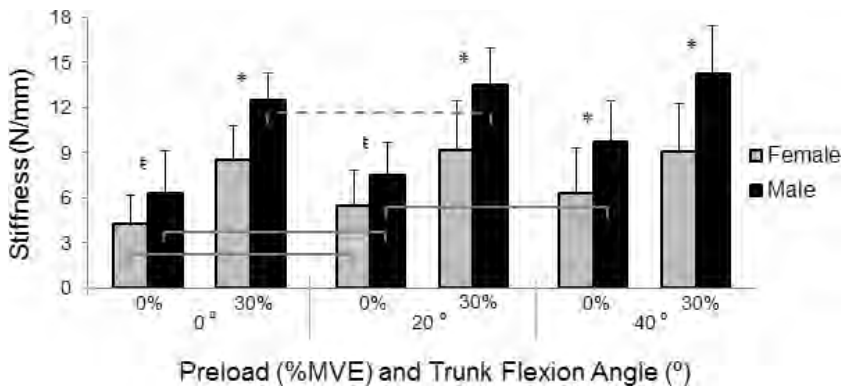

Fig. 3 Intrinsic stiffness of the trunk by gender, preload, and trunk angle. Gender differences at specified levels of preload and angle are denoted with a symbol (* for $p \leq 0.05$ and *t* for $0.05 < p \leq 0.06$). Stiffness comparisons between neighboring trunk angles are denoted by connecting lines (solid for $p \leq 0.05$ and dotted for $0.05 < p \leq 0.06$). Error bars indicate standard deviations.

interaction at each level of trunk angle resulted from increases in gender differences in stiffness as preload increased. At a 0 degree trunk angle, increasing preload from 0 to 30% MVE increased intrinsic stiffness in both males and females, yet stiffness increased 46% more in males than in females. Second, while the gender × trunk angle interaction within the three-way ANOVA approached significance ($p = 0.069$), the gender × trunk angle interaction at each level of preload was significant ($p < 0.001$) and resulted from increasing gender differences with increased trunk angle. At 0% MVE preload, increasing trunk angle from 0 to 40 degrees increased intrinsic stiffness in both males and females, yet stiffness increased 65% more in males than in females. Third, the preload × trunk angle interaction at each level of gender resulted from the effects of trunk angle being dependent upon preload. Across both genders, increasing trunk angle from 0 to 40 degrees increased intrinsic stiffness about 200% more at 0% MVE preload than at 30% MVE preload.

Peak trunk velocity during position perturbations was 8.8% higher in females (mean ± SD: 0.257 ± 0.024 m/s) compared to males (0.236 ± 0.019 m/s) across all conditions ($p = 0.007$), with no effects of preload ($p = 0.957$), trunk angle ($p = 0.561$), or any interactions ($p = 0.134$).

DISCUSSION

The purpose of this study was to investigate the effects of gender, preload, and trunk angle on intrinsic trunk stiffness. Position perturbations were used in an effort to control trunk kinematics and to isolate intrinsic trunk stiffness from reflexive responses. Intrinsic stiffness was lower among females than males within each combination of preload and trunk angle. Intrinsic stiffness also increased more substantially among males than females when increasing preload from 0 to 30% MVE, and when increasing trunk angle across 0, 20, and 40 degrees. Lastly, the effect of increasing trunk angle was diminished at a higher preload.

Despite an expected consistency in trunk kinematics using position-controlled perturbations, peak trunk velocity was 8.8% higher in females than males. This was likely due to: (1) differences in transmissibility of the connecting elements that include properties of soft tissue underneath the harness,[4] and (2) limitations of the motor torque output needed to achieve the desired displacement at a prescribed velocity for male participants (who had higher trunk mass and stiffness). Two considerations, however, suggest that the difference in peak trunk velocity had a minimal effect on the observed gender difference in intrinsic stiffness. First, adding peak trunk velocity as a covariate within the three-way ANOVA for intrinsic trunk stiffness did not change the statistical significance of the effects reported in the results. Second, Bazrgari *et al*.[2] investigated the effects of perturbation velocity (among other experimental factors) on parameters within the same model used here to estimate intrinsic trunk stiffness. Increasing motor rotation frequency from 1.7 to 1.8 Hz, which roughly corresponds to the respective peak trunk velocities measured among males and females in the present study, did not practically affect derived model parameters (e.g. intrinsic stiffness).

Gender differences in intrinsic trunk stiffness found here are consistent with earlier work using position-controlled perturbations[3,13] and testing at a 0 degree trunk angle and 10% MVE preload. However, the current gender differences are inconsistent with prior studies reporting no gender difference in effective trunk stiffness,[6,12] likely a result of methodological differences. For example, Granata and Rogers[12] and Moorhouse and Granata[26] investigated gender differences in effective trunk stiffness using sudden force perturbations (70 and 30 N, respectively). Applying the same magnitude of force to males and females can result in greater and faster trunk flexion in females, who typically have less trunk mass than males. This difference in trunk kinematics (secondary to a gender difference in trunk mass) may have resulted in a gender difference in reflexes, and this gender difference in reflexes could have obscured a potential gender difference in effective stiffness. Moorhouse and Granata[26] also implemented preloads that were absolute rather than relative to strength. While gender differences were found in effective stiffness of the knee when participants held absolute loads,[9] it is possible that using absolute preloads reduces the magnitude of gender differences in effective trunk stiffness.

Increases in intrinsic stiffness with increasing preload and trunk angle found here are consistent with other studies investigating effective trunk stiffness.[12,26] We also observed gender interactions with both preload and trunk angle, as well as an interaction between preload and trunk angle. The gender × preload interaction resulted from intrinsic stiffness increasing with preload more so among males compared to females. This could be due, in part or in whole, to males being stronger than females in trunk extension. Since preloads were relative to strength, males exerted a higher absolute preload (i.e. L_5S_1 moment) compared to females, and effective trunk stiffness increases with increased preload.[21] However, a gender × preload interaction may still exist when using absolute preloads, as shown at the knee.[9] The gender × trunk angle interaction resulted from intrinsic stiffness increasing with trunk angle at a higher rate in males compared to females. Passive tissues in the trunk (e.g. ligaments) exhibit a non-linear increase in stiffness when stretched,[7] including a lower stiffness in the "toe region" of the force-displacement curve where "wavy" collagen fibers straighten out followed by an increase in stiffness as the collagen fibers themselves are stretched. Related to this, passive stiffness of the trunk increases non-linearly with increasing trunk angle.[24] The gender × trunk angle interaction reported here may thus be due to gender differences in this non-linear behavior, as has been shown elsewhere.[24] Lastly, the preload × trunk angle interaction resulted from the increase in intrinsic stiffness with increasing trunk angle diminishing at 30% MVE preload. At 30% MVE preload, more muscle activation is needed at the 0 degree trunk angle to achieve the preload compared to the 40 degree trunk angle (due to the aforementioned non-linear increase in passive trunk stiffness with increasing trunk angle). This varying amount of trunk muscle activation within the 30% MVE preload condition reduces the variation in trunk stiffness across the three trunk angles tested.

Intrinsic stiffness in the baseline condition (0% MVE preload and 0 degree trunk angle) averaged 4.26 ± 1.91 N/mm for females and 6.29 ± 2.84 N/mm for males. These are comparable to the intrinsic stiffness values of 3.54 N/mm for females and 4.91 N/mm for males reported by Hendershot*et al*.[13] who implemented a similar position perturbation method at 10% MVE preload and 0 degrees trunk flexion angle. Comparing intrinsic stiffness values here to effective trunk stiffness elsewhere (at matched preloads and trunk angles), revealed 3–4 times larger intrinsic values. For example, at a 30% MVE preload and 0 degrees trunk angle, intrinsic stiffness measured here averaged 10.58 ± 2.87 N/mm across males and females, while effective stiffness measured using sudden force perturbations at the same preload and trunk angle averaged 3.55 ± 1.13 N/mm.[12] Similarly, at a 30% MVE (average = 104 N) preload and 0 degrees trunk angle, intrinsic stiffness measured here averaged 8.51 ± 2.31 N/mm in females, while effective stiffness in females measured using sudden force perturbations at 100 N preload and 0 degrees trunk angle averaged 2.20 ± 0.61 N/mm.[26] The larger intrinsic stiffness values reported here do not seem intuitive since effective stiffness also includes a reflex contribution. However, other differences in experimental methods likely contributed to these differences in stiffness values. For example, measures of intrinsic stiffness here were obtained over a short ($\sim$40 ms) time interval and $\sim$10 mm trunk motion while earlier measures of effective trunk stiffness were obtained over a longer ($>$500 ms) time interval and $\sim$20 mm trunk motion. Differences in estimated stiffness could also arise from variations in the placement of force and motion sensors, which would affect the range of the spine over which stiffness was measured. In addition to differences in experimental methods, joint dynamics are non-linear and known to vary with the operating state of the joint, defined by the mean torque, perturbation magnitude, mean joint angle, and muscle activity.[17] Linear biomechanical models like the one used here can be used to estimate trunk stiffness as long as measurements are localized to a relatively small operating state.[9] Otherwise, predicted values would represent roughly average properties. The unique capability of the current experimental set up is that it allows for capturing such non-linear behavior of trunk stiffness by controlling for joint angle, muscle activity of mean torque (preload), and perturbation magnitude. However, these stiffness values are still only valid at the range of operating states used here, and therefore it is difficult to compare stiffness values between studies.

In conclusion, females exhibited less intrinsic trunk stiffness than males, and intrinsic stiffness increased more so in males with increasing preload and trunk angle. Overall, these results suggest greater differences in trunk stiffness between males and females when tasks involve various carrying loads and bent postures. Smaller intrinsic stiffness in females, as well as their smaller increases with preload and trunk angle, may contribute to the increased rate of occupational LBP and injury in females.[6,23]

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