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Age related differences in mechanical demands imposed on the lower back by manual material handling tasks

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ABSTRACT

The prevalence of low back pain (LBP) increases with age, yet the underlying mechanism(s) responsible for this remains unclear. To explore the role of biomechanical factors, we investigated age-related differences in lower-back biomechanics during sagittally-symmetric simulated manual material handling tasks. For each task, trunk kinematics and mechanical demand on the lower back were examined, from among 60 participants within five equal-sized and gender-balanced age groups spanning from 20 to 70 years old. The tasks involved lowering a 4.5 kg load from an upright standing posture to both knee height and a fixed height and then lifting the load back to the initial upright posture. During these tasks, segmental body kinematics and ground reaction forces were collected using wireless inertial measurement units and a force platform. Overall, older participants completed the tasks with larger pelvic rotation and smaller lumbar flexion. Such adopted trunk kinematics resulted in larger peak shearing demand at the lower back in older vs. younger participants. These results suggest that older individuals may be at a higher risk for developing lower back pain when completing similar manual material handling tasks, consistent with epidemiological evidence for higher risks of occupational low back pain among this cohort.

1. Introduction

Low back pain (LBP) is the leading cause of disability globally; ahead of 290 other health-related conditions (Buchbinder et al., 2013). Occupationally, 28% of workers develop disabling LBP at some time, with 8% being disabled each year (Manchikanti, 2000), and disabling work-related LBP accounts for ~40% of all lost work days in US industries (Manchikanti, 2000). Healthcare costs related to LBP are also substantial, with annual estimates of ~$100 billion in the U. S. (Katz, 2006). Accordingly, investigating the underlying mechanism (s) responsible for LBP at workplace is essential.

Diverse occupational and non-occupational risk factors have been recognized for LBP (Manchikanti, 2000; Marras, 2000). Among these risk factors, manual material handling (MMH) appears strongly associated with the occurrence of occupational LBP (Garg and Moore, 1991; Hoy et al., 2010; Marras, 2000). Given the physically demanding nature of many MMH tasks, biomechanical loading of the lower back during MMH has been extensively investigated to understand how different MMH parameters may contribute to development of occupational LBP, such as lifting method (Bazrgari et al., 2007), symmetry vs. asymmetry (Arjmand et al., 2010; DeVita et al., 1991; Marras and Davis, 1998), and task dynamics (Buseck et al., 1988; Marras et al., 1993). Convergent findings from these studies and others suggest that excessive mechanical demands on lower back tissues during MMH tasks are likely involved in the causal pathway leading to occupational LBP. However, most reported studies involved younger participants and/or workers, yielding results that may not be generalizable to an older population.

The population of most countries is aging, however, an increasing number of older individuals is remaining in the workforce. In the U.S., for example, nearly a fifth of individuals over 55 (total = ~70 million) were in the workforce in 2008, with projections of 25% (total = ~92 million) by 2018 (Toossi, 2009). Of concern is that the prevalence of LBP increases with age, with reported annual rates of 38% and 12% for older and younger populations, respectively (Bressler et al., 1999; Johannes et al., 2010; Manchikanti, 2000; Peek-Asa et al., 2004). Age-related physiological changes are widely reported, such as reduced muscle strength and joint flexibility (Brown et al., 1994; Hyatt et al., 1990). Such age-related alterations may affect the way an older worker performs MMH tasks and/or the mechanical demand resulting from these tasks. Therefore, the relationship between occupational MMH performance and LBP risk, via biomechanical demands on the lower back, needs to be evaluated for older individuals.

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There are a few reports of age-related differences in MMH biomechanics in the literature (Boocock et al., 2015; Shin et al., 2006; Song and Qu, 2014a, 2014b). All of these earlier studies involved two groups, of young and older individuals, and have generally reported decreased lumbar flexion and increased pelvic rotation among older individuals during lifting. The only aspect of mechanical demand during MMH reported in these studies has been the net moment at the lower back, which was not found to be different between the two age groups (Song and Qu, 2014b). Evidence on age-related changes in trunk strength (Voorbij and Steenbekkers, 2001) and range of motion (Intolo et al., 2009) suggests a nonlinear relationship between aging and MMH biomechanics may be present. Therefore, the main objective of the present study was to more precisely assess age-related differences in work methods and the resultant mechanical demand on the lower back during symmetric MMH tasks. Work methods during simulated MMH tasks were quantified using measures of trunk kinematics (i.e. pelvic and thoracic rotations, lumbar posture and lumbopelvic ratio) and mechanical demand on the lower back was

Table 1
Mean (SD) participant characteristics. Each age group included six male and six female participants.

Age group	Age (years)		Stature (m)		Body mass (kg)	
	M	F	M	F	M	F
22–28	25.6 (1.0)	23.5 (2.3)	177.8 (6.8)	164.9 (3.7)	78.5 (4.7)	61.4 (6.4)
32–38	33.5 (2.2)	34.0 (1.2)	173.0 (5.1)	167.4 (7.1)	81.3 (10.3)	64.5 (10.2)
42–48	44.5 (1.8)	45.1 (1.4)	179.9 (4.8)	166.2 (5.4)	88.0 (12.0)	70.1 (12.1)
52–58	54.3 (1.7)	56.0 (2.3)	180.5 (10.4)	163.4 (6.0)	85.4 (11.3)	72.0 (8.7)
62–68	65.6 (1.6)	65.0 (2.7)	179.7 (6.2)	163.5 (5.7)	86.3 (11.1)	61.0 (4.1)

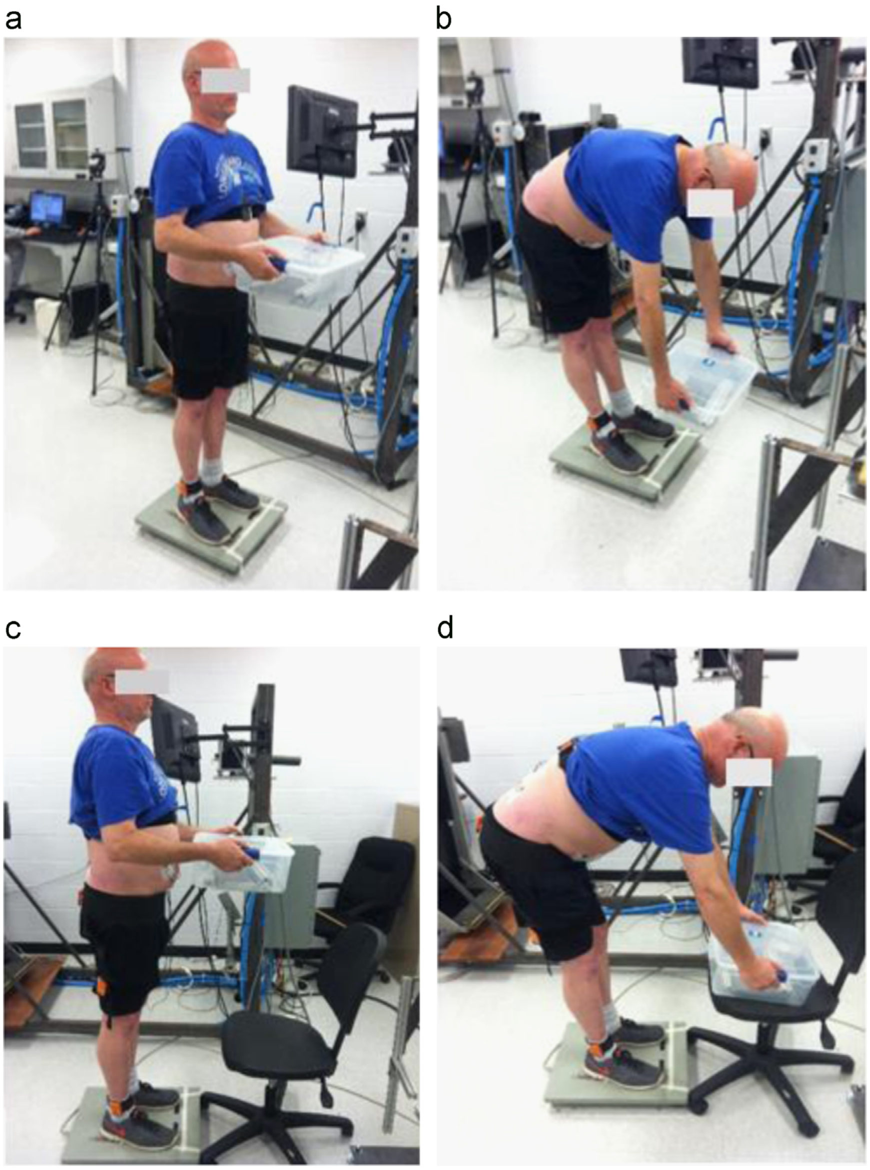

Fig. 1. MMH task procedures: (a) standing posture for Task-1; (b) flexed posture for Task-1; (c) standing posture for Task-2; and (d) flexed posture for Task-2. Note that sensor locations are only for illustration, whereas in the actual experiment they were attached directly to the skin surface.

quantified using estimates of both net moment and forces at the lower back. On the basis of earlier evidence regarding significant functional change in the trunk after the fourth decade of life (Intolo et al., 2009), it was hypothesized that individuals over 50 would adopt trunk kinematics that would lead to larger mechanical demand at the lower back when completing the same MMH task as younger individuals.

2. Method

2.1. Participants

Sixty healthy individuals completed the study, and were recruited to form five equal-sized and gender-balanced age groups: 22–28, 32–38, 42–48, 52–58, and 62–68 years old (Table 1). These age groups were intended to represent individuals in the 1st through 5th decades of working life. Univariate analysis of variance (ANOVA) indicated no significant differences in stature ($p=0.851$) or body mass ($p=0.127$) between the five age groups (Table 1). Participants completed an informed consent procedure approved by the University of Kentucky Institutional Review Board prior to any data collection. All participants reported engaging in regular, moderate levels of physical activity, had a BMI between 22 and 30, and were free from any self-reported musculoskeletal disorders or other medical conditions that might have substantially influenced the experimental results. Individuals with a history of working in physically demanding occupations were excluded, to minimize potential confounding related to prior exposure to LBP risk factors. To avoid potential confounding from LBP-induced changes in trunk neuromuscular behaviors (Ahern et al., 1986; Arendt-Nielsen et al., 1996), individuals with a recent (1 year) history of LBP were also excluded. To recruit the 60 eligible subjects, we screened >200 individuals.

2.2. Experimental procedures

To enhance the reliability of our results, each participant completed two identical experimental sessions, which were conducted in the morning to minimize the influence of diurnal changes in lower back biomechanics (Adams et al., 2007). In each session, participants completed two sagittally-symmetric MMH tasks while standing on the center of a force platform (AMTI, Watertown, MA). The first task (Task-1) involved lowering a 4.5 kg load from an upright standing posture to knee height and then lifting the load back to the initial upright posture (Fig. 1). This task was designed to simulate a MMH tasks with a subject-specific, anthropometrically-designed target height. The second task (Task-2) involved lowering the same load from the upright standing posture and placing it on a horizontal surface (i.e., fixed height for all subjects) located in front of the participant (Fig. 1). In Task-2, to assure the consistency in the amount of load supported by the surface vs. the participant's hand, subjects were instructed to put the load completely on the surface for roughly 2-s. while holding their final lowering posture. This surface was located 55 cm anteriorly and 40 cm superiorly to the center/top of the force platform (Fig. 1). Task-2 was designed to simulate an MMH task with a fixed target height (e.g. placing a load on a horizontal surface with a non-adjustable height). Both tasks were completed using a freestyle method and self-selected pace. All participants completed Task-1 prior to Task-2 and with no practice before the actual testing; however, testing was repeated in cases where the participants violated the task instruction regarding target height. During MMH tasks, trunk and lower-body kinematics were tracked and sampled (50 Hz) using wireless Inertial Measurement Units (IMUs; Xsens Technologies, Enschede, Netherlands), and ground reaction forces were sampled (1000 Hz) from the force platform. Accelerometers were attached to the T10 vertebral process, sacrum (S1), right thigh (superior to the knee joint), and right shank (superior to the ankle joint) using straps. Raw kinematics and kinetics data were low-pass filtered using a fourth-order, bidirectional, Butterworth filter, with respective cutoff frequencies of 6 Hz and 50 Hz (Kristianslund et al., 2012; Hendershot and Wolf, 2014).

2.3. Modeling procedure

A three-dimensional, rigid body, linked-segment model (Freivalds et al., 1984; Kingma et al., 1996) of the lower extremities and pelvis was developed in MATLAB (The MathWorks Inc., Natick, MA, USA, version 7.13) to estimate the net reaction forces and moments at the lower back. The model included seven segments (pelvis and bilateral feet, shanks, and thighs) that were connected using frictionless point-contact joints (Fig. 2). Anthropometric and inertial properties of each segment were estimated from individual stature and mass using existing regression equations (Winter, 2009). Rotation matrices output from IMUs were used to calculate angular velocity and acceleration for each segment using successive numerical differentiation procedure, and linear velocity and acceleration were found using the relationship between linear and rotational velocity and the assumption that the ankle remains in a fixed planar position, which provided a constant reference for the model (Freivalds et al., 1984). Due to task symmetry, similar kinematics was assumed for right and left extremity limbs.

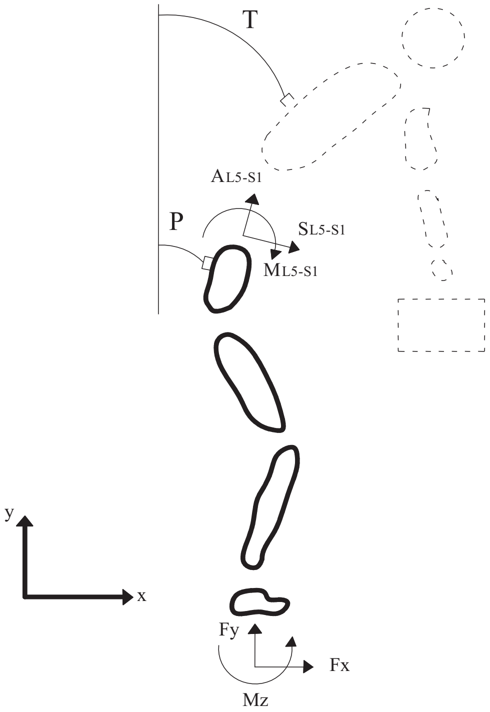

Fig. 2. Lateral view of the linked-segment model. Segments with solid lines were used for "bottom-up" inverse dynamics modeling. $A_{L5\text{-}S1}$, $S_{L5\text{-}S1}$ and $M_{L5\text{-}S1}$ represent axial, shearing and moment demand, respectively, at the lower back. F_x, F_y and M_z denote ground reaction forces. Pelvic (P) and thoracic (T) rotations are shown in the figure.

A bottom-up inverse dynamic approach was used to estimate reaction forces and moments at the lower back (via stepwise estimates at the ankle, knee, and hip joints). Estimated reaction forces and moment at the upper side of the pelvis segment were assumed to represent mechanical demands imposed at the lower back (Freivalds et al., 1984; Song and Qu, 2014b). Projections of the lower back reaction forces perpendicular (i.e., axial) and parallel (i.e., shearing) to the L5-S1 intervertebral disc were calculated to demonstrate the contribution of task demand (i.e., trunk weight and inertia, and external load) to total axial and shearing forces (i.e., sum of external demand and internal tissues response) experienced at the lower back. Following results of Schwab et al. (2006), the orientation of the L5-S1 intervertebral disc in the standing posture was considered to be 51° (with respect to the gravity direction) for the 22–28 and 32–38 age groups, 50° for the 42–48 and 52–58 age groups, and 54° for the 62–68 age group. Since a similar sacral slope in standing posture has been reported between genders (Mac-Thiong et al., 2011), the same values of sacral orientation were used here for males and females. Estimated forces and moments were normalized to body mass and stature*body mass, respectively (Hendershot and Wolf, 2014). However, to present such kinetic measures in a more clinically-meaningful sense (but without affecting the results of statistical analyses), normalized values were multiplied by constants equal to mean body mass and mean stature*body mass across participants. Finally, all kinetic data were time-normalized to a 100% of a lifting task cycle.

2.4. Dependent measures and statistical analysis

The dependent measures included several measures of trunk kinematics and task demands, as well as the duration of self-selected paces. Kinematic outcome measures for each lifting task were the measured pelvic and thoracic rotations along with corresponding values of lumbar flexion and lumbopelvic ratio, all at the time of maximum thoracic rotation. At this time, lumbar flexion was considered to be the difference between the thoracic and pelvic rotations while lumbopelvic ratio was calculated as the ratio of lumbar flexion to pelvic rotation (Granata and Sanford, 2000). Measures of task demands were the maximum values and corresponding timings for axial, shearing and moment demand of the MMH task at the lower back. Preliminary statistical analyses showed no significant difference ($p=0.31$) between the maximum values of task demands during the lowering and lifting phases. Thus, for maximum values with two possible timings, the first half of the task cycle (i.e. lowering phase) was considered for statistical analysis of timings. For each participant and dependent measure, the mean value across two trials (i.e. two sessions) was used for statistical analyses.

Due to the large number of dependent measures, a two-way multivariate analysis of variance (MANOVA) was used to control the experiment-wise error rate

(Swanson and Holton, 2005). For any significant effect of the independent variables (i.e. age group and gender) and their interaction (age*gender) identified by MANOVA, a follow-up univariate two-way ANOVA was performed. Significant univariate ANOVAs were followed by post hoc analyses using Tukey's procedure. Since the two lifting tasks were independently designed, separate statistical analyses were performed for each task. All statistical analyses were performed using SAS (version 9.4, Dell Inc), and summary values are reported as means (SD). In all cases, a p value ≤ 0.05 was considered as statistically significant. However, for cases with violation of parametric model assumptions, the p value 0.05 was reduced to 0.01.

3. Results

From MANOVA, gender ($p<0.001$) and age ($p<0.001$) had significant effects on the set of dependent measures for both tasks, and a non-significant interaction effect ($p=0.143$). During Task-1, the contribution of peak pelvic to peak thoracic rotation was larger ($F=7.12$, $p<0.001$) among older participants, while the contribution of peak lumbar to peak thoracic rotation was smaller ($F=4.53$, $p=0.003$) (Fig. 3). Age-related differences in the relative contributions of pelvic and lumbar to thoracic rotation were also evident in the corresponding lumbopelvic ratios ($F=4.41$, $p=0.004$) during Task-1 (Fig. 3). Similar age-related differences in trunk kinematics (pelvic rotation: $F=2.91$, $p=0.031$; lumbar rotation: $F=6.37$, $p=0.003$; lumbopelvic ratios: $F=4.9$, $p=0.002$) were observed during Task-2 (Fig. 4). For both MMH tasks, thoracic rotations were not different across age groups or genders (Task-1: 87(12)°, Task-2: 81(11)°). In addition to age-related differences, the contribution of peak pelvic to peak thoracic rotation was significantly larger (Task-1: $F=10.97$, $p=0.002$; Task-2: $F=4.63$, $p=0.036$) among female vs. male participants (Task-1: 32 (12)° vs. 24 (10)°; Task-2: 28 (9)° vs. 23 (9)°). Further, the contributions of peak lumbar to peak thoracic rotations were significantly larger among male vs. female participants, at 64(9)° vs. 53(12)° during Task-1 ($F=17.20$, $p<0.001$), and 60(8)° vs. 49(12)° during Task-2 ($F=19.36$, $p<0.001$). Lumbopelvic ratios were also larger among male vs. female participants (3.3(1.9) vs. 2.0(1.5)) during Task-1 ($F=10.15$, $p=0.003$), and 3.1 (1.7) vs. 2.0 (1.1) during Task-2 ($F=9.19$, $p=0.004$).

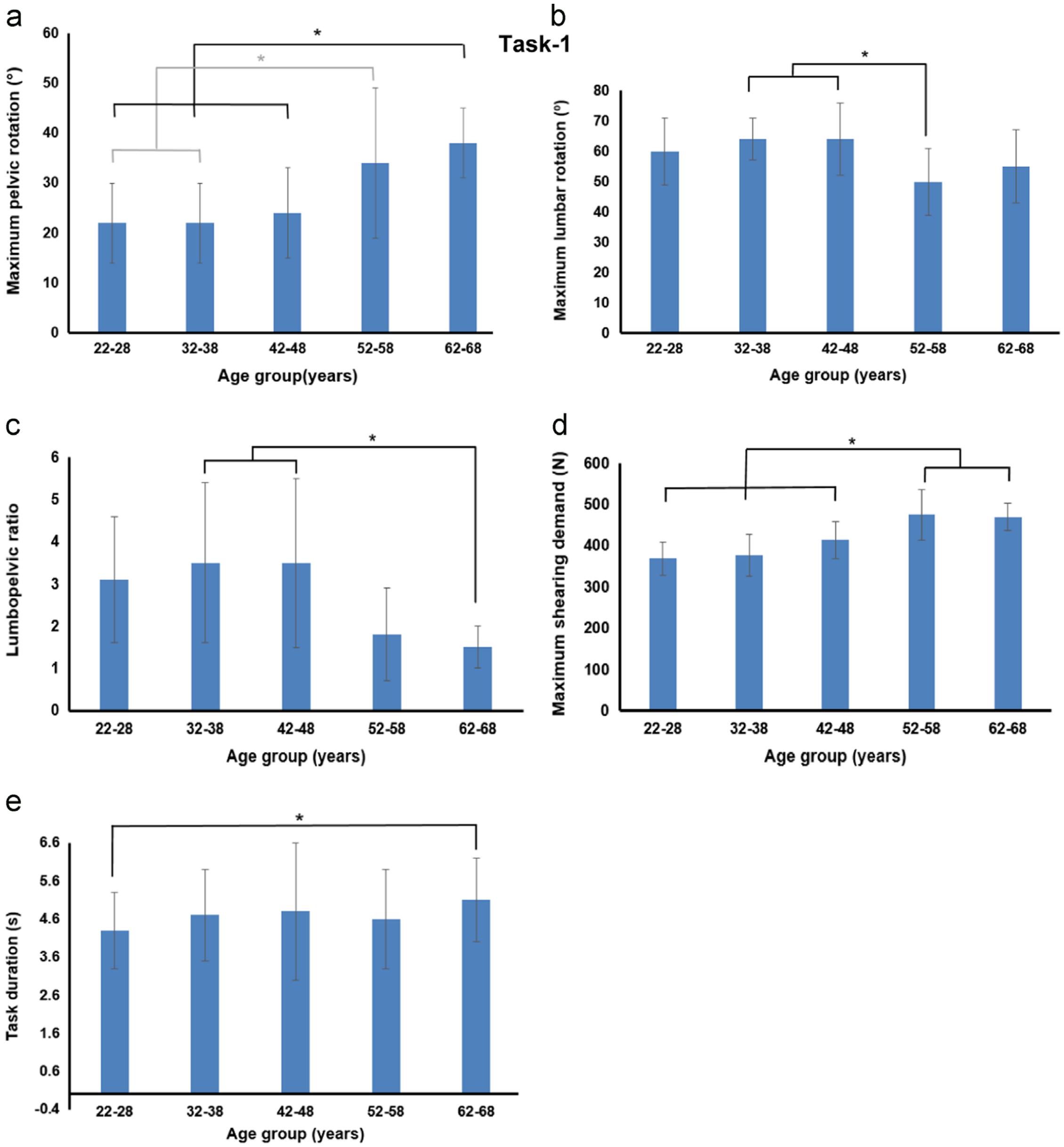

Fig. 3. Age-related differences in: (a) maximum pelvic rotation; (b) maximum lumbar rotation; (c) lumbopelvic ratio at maximum thoracic rotation; (d) maximum shearing demand; and (e) task duration for Task-1. Significant paired differences between age groups are indicated with brackets.

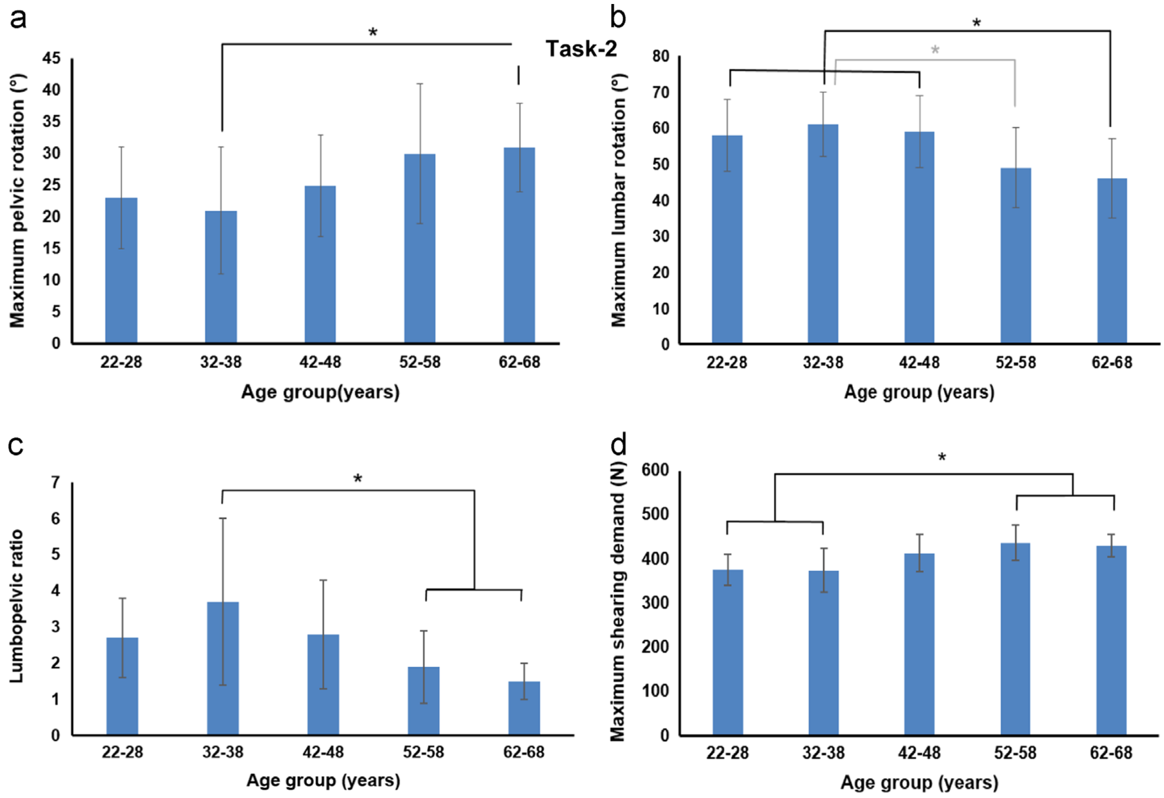

Fig. 4. Age-related differences in: (a) maximum pelvic rotation; (b) maximum lumbar rotation; (c) lumbopelvic ratio at maximum thoracic rotation; and (d) maximum shearing demand for Task-2. Significant paired differences between age groups are indicated with brackets.

Temporal patterns of mean lower back loads for each age group during Task-1 and Task-2 are depicted in Figs. 5 and 6, respectively. For both tasks, there were no significant differences between age groups or genders in the maximum values of net moment (Task-1: 92(23) N m, Task-2: 112(24) N m), axial demands (Task-1 and Task-2: 364(16) N), or the timing of maximum net moment (Task-1: 49 (7)%, Task-2: 31(7)%), axial (Task-1 and Task-2: 4.8(2.5)%) and shearing demands (Task-1: 51(5)%, Task-2: 32(6)%). Shearing demand of the task was, however, larger (Task-1: $F=16.11$, $p<0.001$; Task-2: $F=7.15$, $p=0.001$) among older vs. younger participants in both tasks (Figs. 3 and 4) and among female vs. male participants (Task-1: 435(69) N vs. 406(56) N; Task-2: 419 (42) N vs. 393(48) N) during both tasks (Task-1: $F=6.73$, $p=0.012$; Task-2: $F=6.65$, $p=0.013$). Finally, it took longer ($F=3.57$, $p=0.035$) for older participants to complete Task-1 (Fig. 3), while there were no significant differences in task duration between genders in Task-1 (4.9 (1.3) s) or between age groups or genders in Task-2 (7.7(1.7) s).

4. Discussion

The main purpose of this study was to assess potential age-related differences in trunk kinematics (i.e., measures of work methods) and the resultant mechanical demands on the lower back during two sagittally-symmetric MMH tasks. Five gender-balanced age groups were formed to enable more specific evaluation of age-related differences in MMH biomechanics. Similar levels of maximum thoracic rotation were adopted by participants in both tasks, regardless of age and gender. However, the contribution of pelvic rotation relative to lumbar flexion to such level of thoracic rotation was larger among older participants. Such adopted kinematics resulted in bearing a higher shearing load on the lower back in older participants (i.e., confirming our hypothesis). For both measures of work methods and the resultant mechanical demand, significant differences were observed between individuals older vs. younger than 50 years.

Studying groups of young and older people, Song and Qu (2014b) similarly reported larger pelvic rotation, smaller lumbar flexion, and similar thoracic rotation among older individuals when performing various symmetric MMH tasks. Shin et al. (2006) also reported smaller lumbar flexion among older individuals during sagittally symmetric MMH tasks; a difference that was not statistically significant, though, likely due to the small sample size. These studies suggested that larger pelvic rotation and smaller lumbar rotation among older individuals might be a protecting strategy for reducing the moment demand of the task on the lower back tissues. This suggestion, though, seems unlikely given their reported results and our current ones indicating similar or larger moments at the lower back of older individuals. Alternatively, such age-related differences in the work methods could be a natural response of the neuromuscular system to changes in the musculoskeletal system with aging, such as a stiffer lumbar spine and weaker back muscles (Adams et al., 2007), that make it more demanding to flex the lumbar spine vs. rotating the pelvis. This reasoning may also help explain the observed age-related differences in the duration of Task-1.

The lumbopelvic ratio found in our youngest age group, 2.9 (1.3), was consistent with the reported value of 2.5 (2.4) by Granata and Sanford (2000) that was obtained from relatively young participants (mean age (SD): 23.8 (3.1)) while lifting a 10 kg load. Estimation of lumbopelvic ratio from data reported by Song and Qu (2014b) resulted in values of 3.2 and 1 in the younger and older groups, respectively, comparable with ratios of 2.9(1.3) and 1.5 (0.5) here. Contrary to the earlier suggestion (Song and Qu, 2014b), rather than being a protecting strategy, age-related differences in work methods may predispose older individuals to a higher risk for LBP. A changed (larger or smaller) lumbopelvic ratio

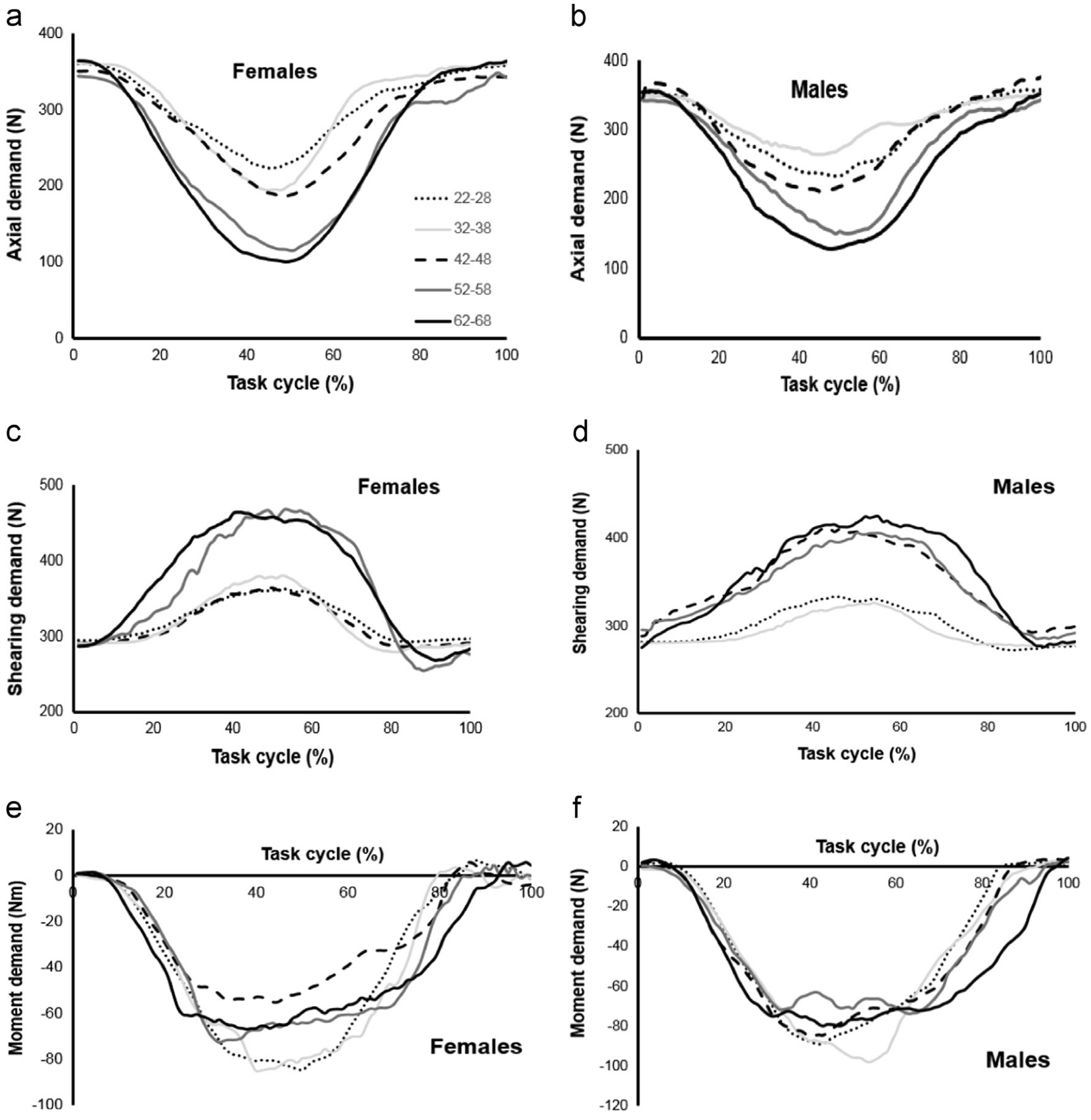

Fig. 5. Mean values of axial, shearing, and moment demands of Task-1 at the lower back for different age and gender groups.

relative to the "normal" condition (healthy individuals), as seen in our study among older (higher reports of LBP) vs. younger and female (higher reports of LBP) vs. male participants (Bressler et al., 1999; Johannes et al., 2010), has been suggested as a clinical indicator of higher LBP risk (Esola et al., 1996; Kim et al., 2013). This suggestion is consistent with higher reports of LBP among older individuals and females (Johannes et al., 2010). From a biomechanical point of view, our results suggest that such age-related differences in work methods impose a higher risk of injury not due to moment demands imposed by the task (to be balanced by lower back tissues) but due to the task-related shearing demand (to be balanced by facet joints and intervertebral disks).

Though we have not accounted for the effects of internal tissue response to task demand on the lower back loading, it should be mentioned that larger pelvic rotation at similar thoracic rotation among older individuals causes the shearing projection of internal tissues response to moment demand of the task to act in the same direction (posterior–anterior) of shearing demand of the task (Arjmand and Shirazi-Adl, 2005), therefore substantially increasing the shearing force acting on the lumbar spine. Furthermore, using a finite element simulation, Tafazzol et al. (2014) showed that a decrease in lumbopelvic ratio resulted in higher shearing and compression forces at the L5-S1 disc. Considering the smaller lumbopelvic ratios in older vs. younger individuals in our study, the former likely experience even higher total spinal loads after accounting for the effects of internal tissue responses to the task demand (Tafazzol et al., 2014). Given the principal role of facet joints in resisting shearing forces (Adams et al., 2007), our findings are consistent with a higher prevalence of LBP due to facet joint pain in older individuals.

There are several limitations associated with our study that should be kept in mind when interpreting the reported results. First, the MMH tasks were performed with a self-selected pace in the sagittal plane. Both velocity and asymmetry of trunk motion have been suggested to affect lower back mechanics, but were not investigated here. Second, symmetry of lower extremity kinematics was assumed, with only data from the right side used in the linked-segment model. Given the sagittal symmetry of the current MMH tasks, though, this assumption was not expected to have introduced substantial error. Third, we did not exclude individuals who had a history of LBP more than one year prior to the study. Any persistent LBP-related alterations in trunk neuromuscular

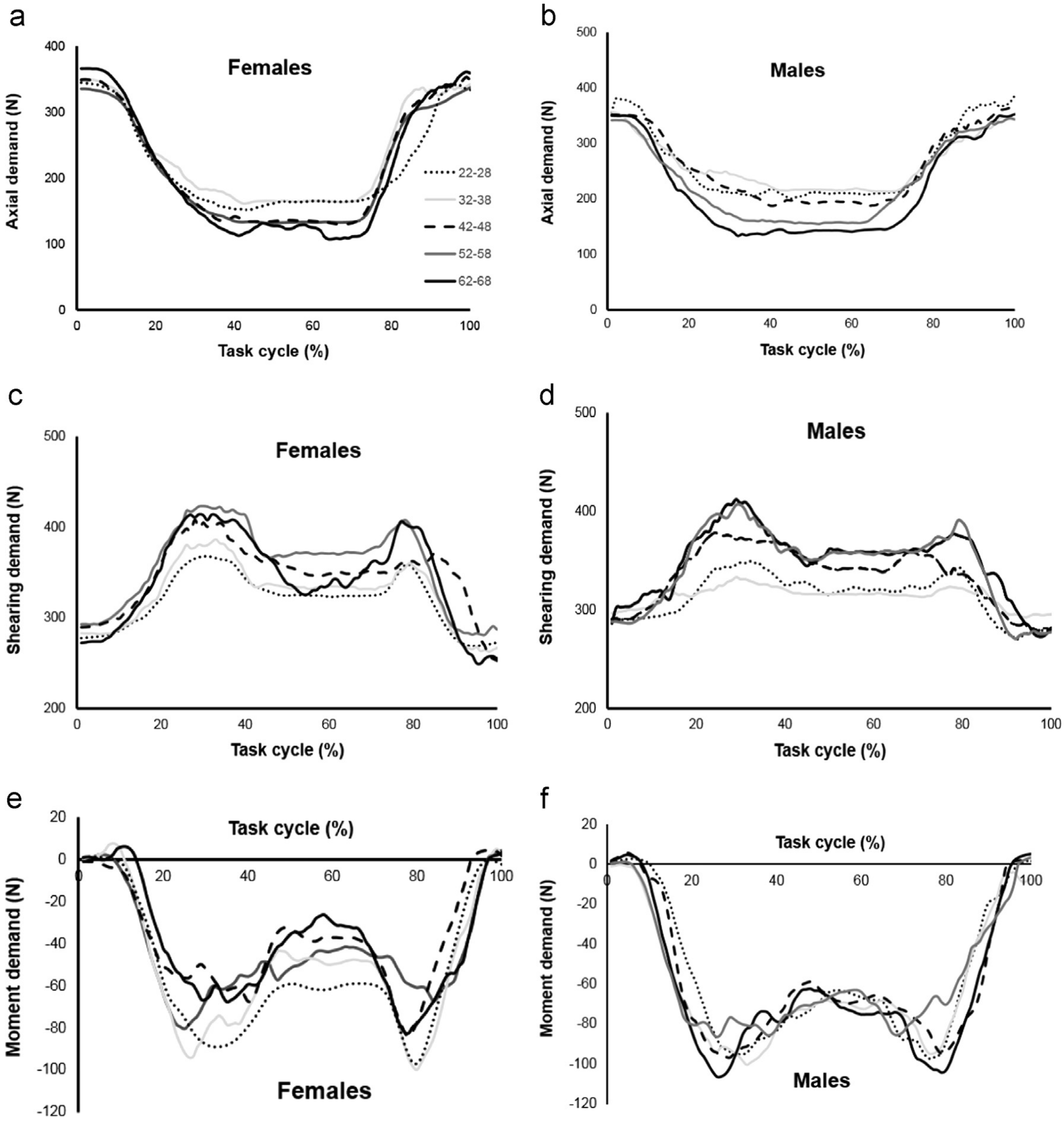

Fig. 6. Mean values of axial, shearing and moment demands of Task-2 at the lower back for different age and gender groups.

behavior could thus have impacted our results. Fourth, the reported loading at the lower back only represents the task demand; more detailed models should be used for characterizing the internal tissue responses and estimating spinal loads using the resultant muscle forces. Finally, potential sources of error in our analyses could have affected the accuracy of low back load estimates, including experimental errors (e.g., skin movement artifact and misalignment of IMU axes with joint rotation axes) and modeling errors (e.g., modeling assumptions related to anthropometric measures and point contact at joints). Given that we did not measure the kinematics of the whole body or the exerted forces at the hands, we could not determine the accuracy of our modeling predictions via comparison of predicted vs. measured kinetics at either end of the kinematic chain (Riemer et al., 2008). A comparison of top-down vs. bottom-up calculations of lower back loads, which has also been used to investigate the validity of estimated loads (Kingma et al., 1996; Hendershot and Wolf, 2014; Plamondon et al., 1996) was similarly impossible.

In summary, our outcomes for the work methods and resultant demands were in general different between the three younger groups and the two older groups. The mechanical behavior of lower back tissues and the prevalence of LBP have been reported to significantly alter after the fourth decade of the life (Manchikanti, 2000). Our results suggest that such age-related differences in mechanical behavior of lower back tissue result in adaptation of work methods that can predispose individuals to a higher risk of spinal injury and LBP.

Conflict of interest statement

We declare that all authors have no financial or personal relationships with other persons or organizations that might inappropriately influence our work presented therein.

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