Human Movement Science 30 (2011) 574–583

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Age and gender moderate the effects of localized muscle fatigue on lower extremity joint torques used during quiet stance

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ARTICLE INFO

Article history:
Available online 26 January 2011

PsycINFO classification:
4010 Human factors engineering

Keywords:
Equilibrium
Working conditions
Fatigue
Aging
Physical strength

ABSTRACT

This study examined the effects of localized muscle fatigue, age, and gender on lower extremity joint torques used during quiet stance. Thirty-two participants performed exercises designed to fatigue the ankle plantarflexors, knee extensors, torso extensors, or shoulder flexors. Body kinematics and ground reaction forces were obtained both before and after the exercises, and joint torques were derived via inverse dynamics. Single joint fatigue affected torque variability at all lower extremity joints, with similar changes for both age groups. Males and females exhibited increased ankle torque variability after different tasks, with males showing more variability after ankle fatigue and females after shoulder and lumbar fatigue. Correlations between peak torques and torque variability differed between males and females and between age groups in certain cases. The results of this study suggested that both age and gender moderate the effects of fatigue on postural control and should be considered when developing strategies to prevent occupational falls.

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doi:10.1016/j.humov.2010.03.008

1. Introduction

Work-related falls remain an important cause of injuries and fatalities, even after considerable efforts to improve workplace safety. Falls accounted for more than 20% of nonfatal occupational injuries and were the second leading cause of occupational fatalities in the United States (BLS, 2007a, 2007b). Population projections suggested an increase of about 46% in the number of older workers between the ages of 55 and 64 years between 2000 and 2010 (Horrigan, 2004), so the aging worker population also has to be considered in assessing the risks and prevention of work-related falls.

Hsiao and Simeonov (2001) suggested that most occupational falls result from a loss of balance, and that slips, trips, and imbalance are the most commonly reported initiating factors. Postural instability has been cited as being the best single predictor of falls (Kellog International Work Group, 1987). The postural control system is a dynamic feedback control system that incorporates visual, vestibular, and somatosensory information, as well as the motor system and central nervous system integration (Fransson, Kristinsdottir, Hafstrom, Magnusson, & Johansson, 2004; Fransson, Magnusson, & Johansson, 1998; Horak, 2006). Muscle fatigue has been identified as one factor having detrimental effects on balance control (Hsiao & Simeonov, 2001), and many studies have shown that tasks fatiguing isolated muscle groups can impair postural control. These studies have included real-world tasks such as prolonged cycling and running (Derave, De Clercq, Bouckaert, & Pannier, 1998; Lepers, Bigard, Diard, Gouteyron, & Guezennec, 1997), as well as laboratory-induced fatigue in body segments such as the ankle (Corbeil, Blouin, Begin, Nougier, & Teasdale, 2003; Ledin, Fransson, & Magnusson, 2004; Lundin, Feverbach & Grabiner, 1993; Ochsendorf, Mattacola, & Arnold, 2000; Pinsault & Vuillerme, 2008; Vuillerme & Nougier, 2003; Vuillerme, Burdet, Isableu, & Demetz, 2006; Vuillerme and Demetz, 2007; Yaggie & McGregor, 2002), torso (Davidson, Madigan, & Nussbaum, 2004; Vuillerme and Pinsault, 2007; Vuillerme et al., 2008), neck (Schieppati, Nardone, & Schmid, 2003; Vuillerme, Pinsault, & Vaillant, 2005), and shoulder (Nussbaum, 2003). Age-related decrements in postural control have been demonstrated by a number of groups (Baloh, Spain, Socotch, Jacobson, & Bell, 1995; DuPasquier et al., 2003; Maki, Holliday, & Fernie, 1990; Norris, Marsh, Smith, Kohut, & Miller, 2005; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996; Stelmach, Phillips, DiFabio, & Teasdale, 1989), and age-related differences in the effects of muscle fatigue on various performance measures have also been shown (Bilodeau, Henderson, Nolta, Pursley, & Sandfort, 2001; Lanza, Russ, & Kent-Braun, 2004; Yamada et al., 2000; Yassierli & Nussbaum, 2007; Yassierli, Nussbaum, Iridiastadi, & Wojcik, 2007). Lin et al. (2009) recently compared the effects of fatiguing different isolated muscle groups on postural sway, finding the most substantial effects at the low back and ankle, and also demonstrating that older participants took longer to recover than did a younger group.

While previous studies of isolated muscle fatigue have examined its effects on various measures of postural control, we are not aware of any previous studies that have assessed the lower extremity joint torques that drive fatigue-related kinematic changes in postural sway in either young or old populations. Human motions are generated by muscle forces, which produce torques that move joints through their ranges of motion. Inverse dynamics analysis of the total torque at a joint is thus a powerful tool for gaining insight into the motor control patterns and strength requirements for specific musculoskeletal tasks (Winter, 1990; Zernicke, 1996). Age-related differences have been shown in the joint torques used when maintaining standing balance after support surface perturbations (Gu, Schultz, Shepard, & Alexander, 1996), and both age- and gender-related torque differences have been demonstrated when regaining balance after an induced forward fall (Wojcik, Thelen, Schultz, Ashton-Miller, & Alexander, 2001). Older adults also exhibit slower rates of lower extremity torque development (Thelen, Schultz, Alexander, & Ashton-Miller, 1996), which could have implications for maintaining balance if fatigue alters the amount of strength available at a given joint and forces a rapid adjustment from the preferred postural control strategy.

Given the known influence of localized muscle fatigue on postural control, age-related differences in responses to localized muscle fatigue, and age-related and gender-related differences in joint torques used in maintaining balance, it was hypothesized that age-related and gender-related differences would exist in the lower extremity joint torques used to maintain upright standing posture after individual muscle groups are fatigued.

2. Methods

The present study is a secondary analysis of an experiment reported previously (Lin et al., 2009). As such, a summary of the protocol is given here, and the reader is referred to the noted report for additional details. Thirty-two healthy individuals from the University and local community volunteered for the study (Table 1). Participants had no self-reported injuries, illnesses, musculoskeletal disorders, or occurrences of falls in the past year. All participants completed an informed consent procedure that was approved by the University Institutional Review Board.

Quiet upright stance trials were conducted while participants stood on a force platform (AMTI OR6-7-1000, Watertown, MA) with their eyes closed, feet together, and arms relaxed at their sides. Force platform outputs were sampled at 100 Hz. Retroreflective spherical markers ($n = 18$) were used to track body segment kinematics. Marker locations were collected at 20 Hz with a passive motion capture system (Vicon Motion Systems, Inc., Lake Forest, CA). Each trial was 75 s in duration, with the first 10 and last five seconds being discarded. Data were low-pass filtered using a fourth-order, zero-lag Butterworth filter with a cutoff frequency of 5 Hz, and force platform data were downsampled to 20 Hz.

Separate sessions – corresponding to ankle, knee, torso, and shoulder fatigue – were completed by each participant, with a minimum of two days between each session. All participants completed an initial practice session, and the order of the remaining sessions was counterbalanced using Latin Squares. Maximum voluntary contractions (MVCs) were measured and localized muscle fatigue was induced concentrically in the ankle plantarflexors, knee extensors, lumbar extensors, and shoulder flexors. After an initial warm-up, three pre-fatigue stance trials were completed with at least 1 min of rest between each. These pre-fatigue trials were followed by at least five isokinetic (60°/s) MVCs, using the dominant limb over a 45° range of motion, using a dynamometer (Biodex 3 Pro, Biodex Medical Systems Inc., Shirley, NY). MVCs were recorded as peak joint torques, with corrections for the gravitational effects of dynamometer attachments and body segment masses.

Using the dynamometer, the fatiguing protocol involved repetitive isotonic exertions, again using the dominant limb. These exertions were performed at 60% of the participant's MVC, over the same range of motion as MVCs, and at 12 repetitions per minute. After 2 min, isokinetic MVCs were measured again. If the resulting peak torque was greater than the baseline value (e.g., due to warm-up effects), the isotonic exercises were adjusted to be 60% of the new value. The same process was repeated after 10 min. Exercises were terminated when participants were unable to complete the entire range of motion in three successive repetitions. A final isokinetic MVC was subsequently conducted, and within 45 s participants started the first post-fatigue standing trial. Additional recovery (post-fatigue) trials were recorded at 2, 4, 6, 8, 11, 14, 17, 20, 25, and 30 min after the final MVC. In contrast to the consistent patterns of recovery observed in center-of-pressure data (Lin et al., 2009), similar patterns were not evident in the joint torques calculated for the first several post-fatigue data points. Hence, only the first three post-fatigue trials are included for analysis here.

Kinetic and kinematic data were processed through a two-dimensional inverse dynamics algorithm (Winter, 1990) implemented in MATLAB (The MathWorks, Natick, MA) to determine reactive (internal) joint torques in the sagittal plane at the ankle, knee, and hip. Joint centers, body segment centers of mass locations, and moments of inertia were estimated using existing data (de Leva, 1996). From each standing trial, dependent variables were derived from the variability (standard deviation) and extreme values (max and min). The former was intended to reflect the involvement of a given joint

Table 1
Participant demographics and anthropometry. Data are means (SD). $N = 8$ within each of the four Age × Gender combinations.

		Age (yrs)	Stature (cm)	Body mass (kg)
Younger	Female	21.5 (2.0)	166.1 (56.2)	59.6 (5.1)
	Male	20.4 (1.4)	176.1 (4.6)	74.4 (12.1)
Older	Female	60.8 (6.4)	160.2 (7.5)	66.2 (15.8)
	Male	65.6 (3.8)	175.5 (8.1)	88.9 (13.3)

in postural control, and the latter as an indication of peak muscular demands. Nearly all joint torques were in ankle plantarflexion, knee extension, and hip extension. As such, only peak values in these respective directions were analyzed. Of the 768 total trials (32 participants × 4 joints × 6 trials), nine did not yield reliable results due to poor marker data; these trials were distributed in no apparent pattern across participants and conditions. Two additional trials in which the torque measures were clear outliers (Kutner, Nachtsheim, Neter, & Li, 2005) were also removed from the analysis.

Peak torques were well approximated by a normal distribution, while all torque variations were log transformed to obtain normality (summary statistics for the latter are presented below in the original units). A preliminary multivariate analyses of variance (MANOVA) was conducted to determine if there were significant differences among the three pre-fatigue and three post-fatigue trials. No significant effects were found ($p > .72$); hence, order effects were considered minimal and the replications within each set of pre- and post-fatigue trials were treated as equivalent. In addition, a mixed-factor analysis of variance (ANOVA) was used to assess whether there were differences between age groups and gender in fatigue-induced decrements in isokinetic joint torques. This analysis was done using the proportional difference in torques (change in torque/pre-fatigue torque). None of the main or interactive effects were significant ($p > .31$), and it was concluded that each of the age and gender groups were fatigued to roughly comparable levels. Subsequently, four-way mixed-factor ANOVAs were used to assess the effects of age, gender, joint (fatigue location), and fatigue (post versus pre) on each dependent measure. Bivariate coefficients of correlation (ρ) were also obtained among the dependent measures. Criteria for significance were set at $p < .01$ in the ANOVAs and correlations (relatively conservative, to control for inflation of Type I error).

3. Results

3.1. Pre-fatigue joint torques

No differences in torque variability were found between the two age groups ($p > .49$). Significant differences in knee ($F(1.28) = 9.98$, $p = .0038$) and hip ($F(1.28) = 18.25$, $p = .0002$) torque variability, however, were evident between genders (Fig. 1), with males having 49% and 69% higher variability at these respective joints. Although not significant ($F(1.28) = 4.62$, $p = .040$), males also had 37% higher variability at the ankle. The Age × Gender interaction effect was not significant for torque variability at any of the joints ($p > .38$).

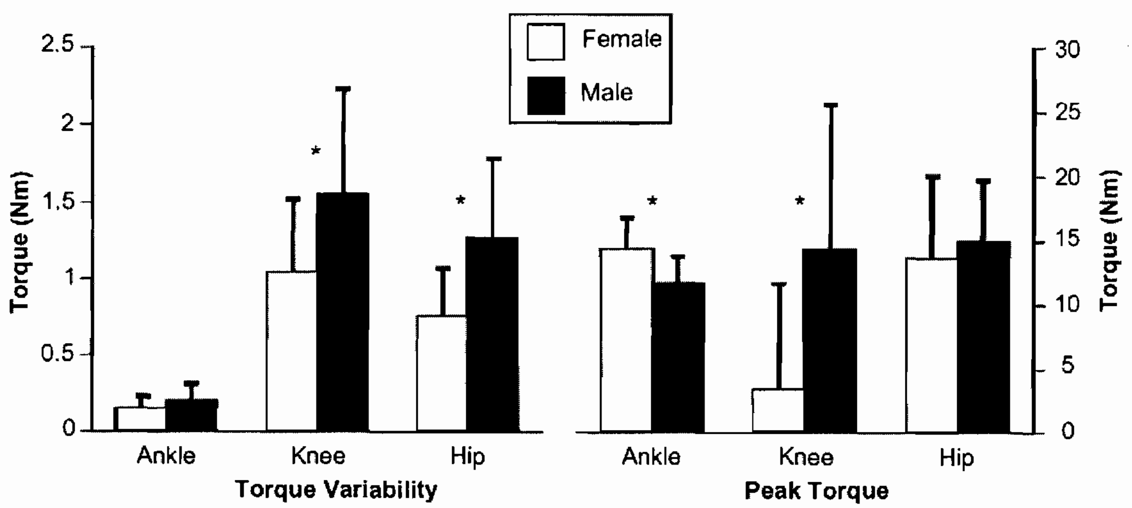

Fig. 1. Effects of gender on torque variability (left) and peak values (right) during pre-fatigue trials. Reactive moments are shown in ankle plantarflexion, knee extension, and hip extension). Error bars indicate standard deviations. The symbol * indicates a significant difference between genders. Males exhibited more torque variability at the knee and hip and used larger peak torques at the knee, while females used larger peak torques at the ankle.

A similar pattern of age and gender effects was found for peak joint torques. Though not significant ($F(1.28) = 2.78$, $p = .11$), peak knee torques were nearly twice as large among the older group. Age-related differences in peak ankle and hip torques, though, were minimal ($p > .34$). Gender differences were found (Fig. 1), with females having 23% higher peak ankle torques ($F(1.28) = 11.02$, $p = .0025$) and males having substantially (326%) higher peak knee torques ($F(1.28) = 11.14$, $p = .0024$). Peak hip torques, however, were similar ($F(1.28) = 0.56$, $p = .46$). There were no Age × Gender interaction effects on peak torques ($p > .59$).

3.2. Fatigue effects on joint torques

Fatigue had significant main effects on the variability of ankle ($F(1.697) = 12.71$, $p = .0004$), knee ($F(1.697) = 21.75$, $p < .0001$), and hip ($F(1.697) = 23.09$, $p < .0001$) torques. Respective increases in variability post-fatigue were 7.8%, 14%, and 12%. Though the Gender × Fatigue interaction was not significant ($F(1.697) = 4.16$, $p = .043$), males had larger (16%) fatigue-induced increases in knee torque variability than females (12%), and a similar trend for hip torque variability. Effects of fatigue on torque variability were otherwise consistent between age and gender groups for all three joints ($p > .043$).

Fatigue location significantly influenced fatigue-induced changes in torque variability at the knee ($F(3.697) = 9.13$, $p < .0001$) and hip ($F(3.697) = 10.30$, $p < .0001$) as summarized in Fig. 2. Torso (lumbar extensor) fatigue led to the largest increases (30–40%) in torque variability at these joints, and also had the largest effects at the ankle. Of note is the substantial inter-individual variability in the effects of fatigue. These joint-specific fatigue effects were generally consistent for both age groups ($p > .049$). In contrast, there was a significant second-order interaction effect of Gender × Joint × Fatigue ($F(3.697) = 3.84$, $p = .0096$) on knee torque variability, and trends for the ankle ($F(3.697) = 3.33$, $p = .020$) and hip ($F(3.697) = 3.04$, $p = .029$). These effects were somewhat complex, yet qualitatively suggested that: (1) ankle fatigue increased torque variability at the ankle, knee, and hip among males, with minimal effects among females; (2) knee fatigue increased knee and hip torque variability among males, with little effect among females; (3) shoulder fatigue had minimal effects on torque variability at the knee and hip in both genders, but females had larger fatigue-induced increases in ankle torque variability; and, (4) females had larger increases in joint torque variability in response to torso fatigue, particularly at the ankle (Fig. 3).

Fatigue led to increases in peak torques at all three joints, though these changes were relatively small (<0.6 Nm, and <5%) and all main effects of fatigue were non-significant ($p > .022$). A significant

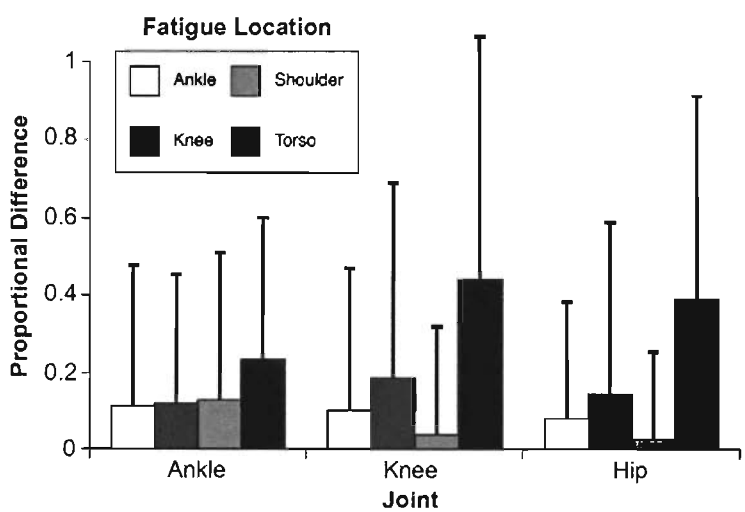

Fig. 2. Effects of fatigue location on torque variability at the ankle, knee, and hip. Values are proportional increases post-fatigue. Error bars indicate standard deviations. Torso (lumbar extensor) fatigue led to significant increases in torque variability at the knee and hip. A significant second-order interaction effect of Gender × Joint × Fatigue was present at the knee.

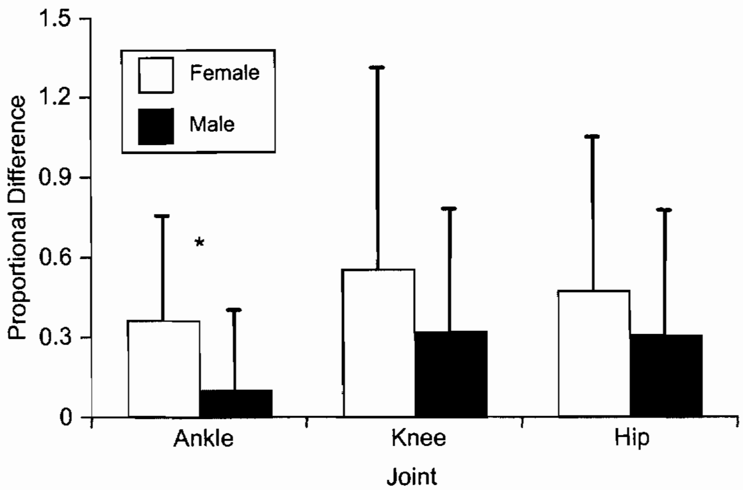

Fig. 3. Gender differences in the effects of torso (lumbar extensor) fatigue on torque variability at the ankle, knee, and hip joints. Values are given as proportional increases post-fatigue. Error bars indicate standard deviations. The symbol * indicates a significant difference between genders. Fatiguing the lumbar extensors caused females to exhibit significantly more post-fatigue ankle torque variability than did males.

Gender × Fatigue effect on peak knee torque was found ($F(1.697) = 7.41$, $p = .0066$): post-fatigue decreases in peak knee torque were somewhat (~10%) larger among females. No other significant interactive effects ($p > .03$) or patterns were evident.

3.3. Correlations among dependent torque measures

Significant correlations (ρ) were found among the several torque measures (Table 2). Overall, torque variations at the three joints were positively correlated, and those for the hip and knee quite highly. Positive correlations were also evident among the peak torques. Peak ankle and hip torques were negatively correlated with torque variations at all three joints, while a positive correlation was found for peak knee torque and torque variations.

This pattern of correlations was qualitatively and quantitatively similar across both genders, with one exception. Among males, maximal ankle and knee torques were negatively correlated ($\rho = -.58$), with a non-significant result for females ($\rho = .02$). Several differences in these correlations existed between the two age groups. Among the younger participants, variability in both knee and hip torques were weakly ($\rho \sim .10$) and positively correlated with peak ankle and hip torques, and strongly ($\rho \sim .70$) and positively correlated with peak knee torques. In contrast, among the older group both knee and hip torque variability were moderately and negatively correlated with peak ankle torque ($\rho \sim -.23$), moderately and positively correlated with peak knee torque ($\rho \sim .23$), and more strongly and negatively correlated with peak hip torque ($\rho \sim -.56$). No influences of fatigue were evident on the patterns of correlations among the variables.

Table 2
Bivariate coefficients of correlation (ρ) among the pairs of torque measures (peak values and variability). Bolded values are significant ($p < .01$).

	Var. ankle	Var. knee	Var. hip	Peak ankle	Peak knee
Var. knee	**.53**				
Var. hip	**.57**	**.98**			
Peak ankle	**−.27**	−.06	−.03		
Peak knee	**.34**	**.43**	**.47**	**.57**	
Peak hip	**−.24**	**−.27**	**−.31**	**.22**	**.51**

4. Discussion and conclusions

The present study was designed to determine whether localized muscle fatigue in four muscle groups (ankle plantarflexors, knee extensors, lumbar extensors, and shoulder flexors) affected the lower extremity joint torques used to maintain upright stance. Also of interest was whether there were age-related or gender-related differences in these effects. An examination of ankle plantarflexion, knee extension, and hip extension torques showed that muscle fatigue increased torque variability in all lower extremity joints for both younger and older adults, particularly at the knee and hip.

Gender differences in pre-fatigue joint torque magnitudes were seen in the current study, primarily at the knee. Along with this difference in torque magnitude, gender differences in the effects of fatigue on torque variability suggest that there were differences in the organization of postural control between males and females. Increased ankle torque variability was seen in males after ankle fatigue and in females after shoulder and lumbar fatigue. Given that control of ankle torques contributes to the maintenance of balance after unexpected postural perturbations (Runge, Shupert, Horak, & Zajac, 1999), then these differences in ankle torque variability might imply that female workers could be more prone to falls after tasks that fatigue the upper body, while males might be more sensitive to tasks that fatigue the lower body. Males also showed increases in knee and hip torque variability after ankle and knee fatigue, while females did not. In addition to these differences in torque variability, males showed a negative correlation between maximal ankle and knee torques, while females did not. It is not clear whether these differences are related to anthropometric, physiological, preferred postural strategy, or anticipation differences between the gender groups.

We did not find any differential age effects on the magnitudes or variability of lower extremity joint torques used to maintain upright stance after the different muscle groups were fatigued, but both older and younger participants did show increases in post-fatigue joint torque variability. These increases in variability could be more significant from a functional perspective for older workers than for the young. In a study by King, Luchies, Stylianou, and McVey (2007), fatiguing the ankle joint resulted in a decrease in the rate of torque development at the ankle in young participants, but not in the older group. King et al. also found, however, that pre-fatigue rates of torque development were slower for older participants at both the ankle and knee. Slower rates of torque development at any of the lower extremity joints could have implications for tasks in which fast responses to postural disturbances are important. The fact that older adults generally start with lower baseline values for muscle strength (Schultz, 1992) and rates of torque development (Thelen et al., 1996), as well as the fact that older participants exhibit slower post-fatigue recovery rates in quiet stance (Lin et al., 2009), suggests that stressing older workers with larger physical loads, more extensive fatigue, or shorter rest periods could cause them to reach maximum physical capacity and be more prone to a fall under different conditions than would younger workers.

While most postural control models focus largely on ankle and hip strategies for maintaining stance, this study indicated a considerable amount of post-fatigue knee torque variability for the knee. Given that knee torque variability increased during a simple standing task after fatiguing the ankle, knee, or lumbar musculature, it appears that considering only ankle and hip activity in models of postural control might be limiting. It is not clear whether ankle fatigue (Kwon, Choi, Yi, & Kwon, 1998; Lin et al., 2009) or knee fatigue (Gribble & Hertel, 2004) has a larger effect on basic postural stability. Most knee motion is considered to be a minor factor in maintaining upright stance, but the knee musculature is crucial to the performance of larger-scale motions. In more challenging activities, knee extensor fatigue has been shown to alter both takeoff and landing mechanics during single-leg hops (Augustsson et al., 2006), and control of knee motion is compromised when landing after a fatigued single-leg hop (Orishimo & Kremenic, 2006). Lower extremity fatigue also delays activation of knee musculature when executing a rapid stop while running, and the knee might be the primary site of fatigue-related force losses during this activity (Nyland, Shapiro, Stine, Horn, & Ireland, 1994). It is clear that fatiguing any of the lower extremity or lumbar muscle groups has the potential to affect knee function, which could increase the likelihood of injury if rapid whole-body motions are required while an individual or worker is in a fatigued state.

A number of limitations of the current study warrant discussion. First, only one joint of each pair was fatigued at the ankle, knee, and shoulders. Fatiguing joints bilaterally might have led to more significant fatigue-related effects on postural control and compensatory torques at other joints, but given that daily and occupational tasks are commonly one-handed or otherwise stress one side of the body more than the other, the unilateral approach taken here seems reasonable. Second, the inverse dynamics analysis was performed only in two dimensions, with each participant's body assumed to be symmetric around the midsagittal axis. Joint torque results could have been affected if a participant was not standing symmetrically during data collection, but right-left position data were averaged in the sagittal plane to control for minor discrepancies. Third, only sagittal plane torques and fore-aft postural control has been examined in this study. A future study of torques controlling lateral postural control would require some modifications to the marker set used and extension of the inverse dynamics algorithm to a third dimension. Fourth, inverse dynamics model calculations of the type used in this study are subject to errors caused by inaccurate estimates of joint centers of rotation and body segment centers, signal noise from the motion capture system or skin movement artifacts, and artifacts arising from numerical differentiation and filtering processes. Given that the same data collection equipment and data processing algorithms were used for all participants, relative age group and gender group differences in biomechanical outcome variables should not have been substantially affected by errors in the calculations of absolute joint torques for each individual person. Fifth, this study was performed with a fairly small number of participants in each age and gender group, and the older participants were healthy, active, and not extremely elderly. It is possible that more substantial age-related effects would have become apparent if more participants were tested or if the older cohort was more aged or more frail.

In summary, fatigue-related changes in joint torque magnitudes and variability were consistent across age groups in this study, yet there appeared to be significant gender-related differences in the post-fatigue balance control strategy adopted by both age groups. Given the amount of torque variability observed between different participants, work guidelines intended to reduce occupational fall risks might be better designed based on individual workers' capabilities rather than on monolithic age and gender group assumptions. Regardless of these high levels of individual variability, isolated lower extremity and torso muscle fatigue did alter the joint torques used by both younger and older participants when maintaining quiet stance. Further research is required to determine whether age would have more of a differential effect on post-fatigue joint torques during more challenging postural tasks.

Acknowledgments

The research presented in this paper was supported by Cooperative Agreement Number RO1 OH007882-01 from the Centers for Disease Control and Prevention (CDC). Contents are solely the responsibility of the authors and do not necessarily represent the official views of the CDC.

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