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ORIGINAL ARTICLE

Acute effects of localized muscle fatigue on postural control and patterns of recovery during upright stance: influence of fatigue location and age

Dingding Lin · Maury A. Nussbaum · Hyang Seol · Navrag B. Singh · Michael L. Madigan · Laura A. Wojcik

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Abstract The purposes of this study were to investigate the effects of fatigue location and age on changes in postural control induced by localized muscle fatigue, as well as the patterns of recovery post-fatigue. Groups of 16 younger (18–25 years) and 16 older (55–65 years) participants performed submaximal isotonic fatiguing exercises involving the unilateral ankle plantar flexors, knee extensors, and shoulder flexors, and bilateral lumbar extensors. Postural control was assessed during quiet upright stance, from center-of-pressure and center-of-mass time series obtained before and after the fatiguing exercises. Acute effects of fatigue differed between joints, with the most substantial effects evident at the lower back, followed by the ankle. Neither knee nor shoulder fatigue resulted in significant effects on postural control. Significant acute effects of fatigue were found only among the younger group. Recovery of postural control post-fatigue was influenced by age, being more rapid in the younger group, but not by fatigue location. Along with existing evidence, these results may facilitate the development of strategies to prevent occupational falls.

Keywords Balance · Postural control · Localized muscle fatigue · Aging · Falls · Recovery

Introduction

Falls are a leading cause of work-related injuries and fatalities. In 2006, falls remained the second most common cause for occupational fatalities, and accounted for over 200,000 (20%) of nonfatal occupational injuries in the United States (BLS 2007a, b). Although the focus of this manuscript is on occupational falls, fall-related problems are also prevalent in the general population, especially among aged individuals (Berg et al. 1997; Rubenstein 2006). Hsiao and Simeonov (2001) suggested that the majority of occupational falls slips, trips, and imbalance episodes can be considered collectively as loss of balance incidents. Postural control involves multiple sensory systems (visual, vestibular, and somatosensory), the motor system, and central nervous system integration (Punakallio 2005; Horak 2006). Impaired postural control, often inferred by increased postural sway, has been shown repeatedly to be associated with an increased falling risk (Fernie et al. 1982; Lichtenstein et al. 1988; Maki et al. 1990; Baloh et al. 1995; Prieto et al. 1996) and predictive of future falls among older individuals (Stel et al. 2003; Bergland and Wyller 2004; Pajala et al. 2008). Therefore, to help prevent falls in the workplace, it is important to ensure that postural control is optimized and/or not impaired by individual, environmental, or task-related influences.

D. Lin · M. A. Nussbaum (✉) · H. Seol
Department of Industrial and Systems Engineering,
Virginia Tech, 250 Durham Hall (0118),
Blacksburg, VA 24061, USA
e-mail: nussbaum@vt.edu

M. A. Nussbaum · M. L. Madigan
Virginia Tech, Wake Forest School of Biomedical Engineering and Science, Virginia Tech, Blacksburg, VA, USA

N. B. Singh
Julius Wolff Institut, Charité,
Universitätsmedizin Berlin, Berlin, Germany

M. L. Madigan
Department of Engineering Science and Mechanics,
Virginia Tech, Blacksburg, VA, USA

L. A. Wojcik
Packer Engineering, Inc., Ann Arbor, MI, USA

Localized muscle fatigue (LMF) is one factor that appears to impair postural control. A number of studies have reported increased postural sway with LMF at the ankle (Lundin et al. 1993; Ochsendorf et al. 2000; Vuillerme et al. 2001; Yaggie and McGregor 2002; Corbeil et al. 2003), lower back (Davidson et al. 2004; Pline et al. 2006; Vuillerme et al. 2007), shoulder (Nussbaum 2003), and neck (Schieppati et al. 2003; Gosselin et al. 2004; Vuillerme et al. 2005). However, all these studies investigated the effects of fatigue to isolated muscle groups (or joints) and used a range of experimental methods and protocols. As such, it is difficult to compare directly the effects of LMF in different muscles or functional groups of muscles.

Several studies have reported the differential effects of LMF at different locations on postural control, with some mixed results (Kwon et al. 1998; Gribble and Hertel 2004a, b; Bellew and Fenter 2006; Salavati et al. 2007). Results from these studies suggest that the effects of fatigue on postural control are specific to the muscle groups recruited and measures of postural control used. Of note, these studies were limited to the lower extremity musculature (ankle, knee, and hip). Allum et al. (1998) have suggested that trunk inputs may be more important in triggering balance corrections, and recent evidence highlights that fatigue of lumber extensors can compromise postural control (Davidson et al. 2004; Pline et al. 2006; Vuillerme et al. 2007). However, no studies have compared the effects of muscle fatigue at the lower extremities to more proximal muscle groups, such as lower back and shoulder. Since fatigue may manifest at a range of body locations during occupational and daily activities, it is important to understand whether differential effects might exist.

Adverse effects of age on postural control have been well documented (Maki et al. 1990; Baloh et al. 1995; Prieto et al. 1996; Du Pasquier et al. 2003; Norris et al. 2005). Existing studies have also suggested age-related differences in muscle fatigue. For example, older individuals have exhibited longer endurance times in sustained elbow flexion (Bilodeau et al. 2001) and shoulder abduction (Yassierli et al. 2007). An age-associated fatigue resistance has been shown repeatedly, with older adults demonstrating less rapid declines in maximum voluntary contractions (MVC) of the ankle dorsiflexors (Lanza et al. 2004) and the shoulder abductors (Yassierli et al. 2007), smaller increases in electromyographic (EMG) amplitude of the elbow flexors (Bilodeau et al. 2001), and slower declines in EMG spectral measures of the ankle dorsiflexors (Yamada et al. 2000) and elbow flexors (Merletti et al. 2002) during isometric contractions. Similar findings have also been reported for isokinetic fatiguing exercises involving the ankle dorsiflexors (Lanza et al. 2004) and shoulder abductors (Yassierli and Nussbaum 2007). Based on this and other existing evidence, it can be expected that the effects of LMF on postural control would differ between age groups.

To our knowledge, only one study (Mademli et al. 2008) has investigated the effects of muscle strength decline induced by fatigue on dynamic stability control among younger and older individuals. In their work, the effects of fatiguing knee contractions were determined on the ability to recover from a simulated fall perturbation. The authors found that younger participants had a higher margin of stability both before and after the fatiguing task, but could not identify any clear fatigue effect in either group. However, previous studies (Owings et al. 2000; Mackey and Robinovitch 2005) have suggested that measures of postural control during quiet stance were not associated with measures of balance recovery from postural disturbances. It is thus still unclear whether or how LMF interacts with age to affect postural control during quiet stance.

This study had two goals. The first was to investigate the effects of LMF induced in four muscle groups (ankle, knee, lower back, and shoulder) on acute changes in and recovery patterns of postural control. The second was to investigate whether there were age-related differences in these acute changes and recovery patterns. It was hypothesized that: (1) fatigue-related decrements in postural control would differ in severity between fatigue locations and age groups, and (2) recovery patterns would differ between fatigue locations and age groups. Results from this work were intended to facilitate the development of strategies to prevent occupational falls related to loss of balance.

Methods

Participants

Thirty-two healthy individuals volunteered from the University and local community with groups consisting of gender-balanced younger ($N = 16$, 18–24 years) and older ($N = 16$, 55–65 years) individuals. Mean (SD) stature and body mass of the younger group was 171.1 (7.0) cm and 67.2 (11.9) kg, respectively, with corresponding values of 167.8 (10.9) cm and 77.6 (18.4) kg for the older group. The older group was intended to represent individuals near the typical end of working life, since the number of workers 55-and-older is projected to grow substantially, at four times the rate of growth of the overall labor force, over the early portion of this century (Toossi 2005). Participants had no self-reported injuries, illnesses, musculoskeletal disorders, or occurrences of falls in the past year. All completed an informed consent procedure approved by the University Institutional Review Board.

Experimental design and procedures

A repeated measures design was employed, in which participants performed multiple trials of quiet, upright stance before and after fatiguing exercises involving the ankle, knee, lower back, or shoulder. These joints were selected since they are all involved in posture maintenance, demands are placed on the associated musculature during a variety of work activities, and existing evidence suggests potential effects of LMF at each location on postural control. Each participant completed five sessions, comprised one initial practice session and four subsequent experimental sessions that involved fatiguing at different joint, with a minimum of 2 days between sessions to avoid residual effects of fatigue. The presentation order of LMF location was counterbalanced using Latin Squares. Each session consisted of pre-fatigue trials of quiet standing, warm-up exercises, maximum voluntary isokinetic contractions (MVIC), fatiguing isotonic exercises, and several post-fatigue trials of quiet standing.

Three pre-fatigue trials of quiet standing were collected to improve reliability over a single observation (Lafond et al. 2004) with a rest period of 1 min between each. Eleven post-fatigue trials were recorded in a roughly exponential progression, at 0.75, 2, 4, 6, 8, 11, 14, 17, and 20 min following termination of the fatiguing exercises. Standing trials lasted 75 s, during which participants stood as still as possible on a force platform (AMTI OR6-7-1000, Watertown, MA, USA), while barefoot, arms at their sides, feet together, head pointed straight ahead, and eyes closed. Repeatability of foot placement between trials was maintained by outlining the feet on poster board placed on the top of the force platform. Kinematic data were collected using a marker tracking system (Vicon 460, Lake Forest, CA, USA). Passive surface markers ($n = 18$) were placed bilaterally over the temple, acromion, iliac crest, lateral malleolus, 5th metatarsal, lateral femoral epicondyle, lateral humeral epicondyle, and lateral styloid of the wrist, and unilaterally over the chin and sternum.

Warm-up exercises consisted of two sets of ten repetitions involving calf-raises for the ankle, squats for the knee, stoops for the lower back, and arm flexion for the shoulder. Concentric MVICs were performed at a single joint during each experimental session (i.e., the joint to be fatigued), and involved either ankle plantarflexion, knee extension, lumbar extension, or shoulder flexion. MVICs were conducted at a speed of 60 deg/s using a dynamometer (System 3 Pro, Biodex Medical Systems, Shirley, NY, USA). Ankle, knee, and shoulder MVICs (and the fatiguing exercises described below) were performed unilaterally, using the participants' self-reported dominant limbs. Participants were coupled to the dynamometer using available attachments for the limbs, in a slightly reclined seated posture, and using a custom fixture for the torso, in an upright posture. MVICs were performed through set range of motion (ROM) of 45°: 15° dorsiflexion–30° plantarflexion for the ankle; 100° flexion–55° flexion for the knee; 45° flexion–the upright posture for the torso; and 0–45° flexion for the shoulder. Participants were instructed to perform the exertions 'as hard and as fast' as possible, and were given non-threatening verbal encouragement. At least five MVICs were performed with a minimum of 1 min of rest between each. MVICs were recorded as the peak torques after adjustment for gravitational effects of body segment and dynamometer attachments masses. If an increasing trend in peak torque was evident at the fifth MVIC, additional MVICs were performed until the performance stabilized. After the MVICs, a rest period of 10 min was provided.

Fatiguing exercises consisted of repetitive submaximal isotonic exertions at 60% of individual- and joint-specific pre-fatigue MVIC, at 12 repetitions/min, through the same ROM as for MVICs. After 2 min of exercise, another MVIC was performed. If the resulting peak torque was greater than the pre-fatigue MVIC, the isotonic exertions were adjusted to be 60% of the new value. This process was repeated again after 10 min of exercise if participants had not exhibited signs of fatigue. Minimal resistance was applied when the joint was returned to its original position. Auditory tones generated by a computer were used to ensure participants performed the exertions at a consistent repetition rate and angular velocity. Non-threatening verbal encouragement was provided during the exercises. These exercises were continued until participants could not perform exertions over the entire ROM for three consecutive repetitions, at which point they were assumed to be fatigued to ~60% of their baseline isokinetic capacity.

Data collection and processing

Triaxial ground reaction forces and moments were sampled from the force platform at 100 Hz, low-pass filtered (Butterworth, 5 Hz cut-off frequency, second order, bi-directional), and transformed to obtain center-of-pressure COP values (Winter 2004). Marker positions were sampled at 20 Hz and low-pass filtered (Butterworth, 5 Hz cut-off frequency, second order, bi-directional). Whole body center-of-mass (COM) location was estimated from a 13-segment model (de Leva 1996). For each standing trial, the initial 10 s and last 5 s of data were removed to avoid initial transients and termination anticipation effects, respectively.

Dependent measures

From the COP time series obtained in each trial, two traditional measures were determined (Prieto et al. 1996), namely, ellipse area (EA) and mean velocity (MV). Several more recently defined measures were also included in the analysis. Time-to-boundary (Ttb) was used to estimate the time at which COP would reach the stability boundary, given its instantaneous trajectory and velocity (van Wegen et al. 2002; Hertel et al. 2006). During standing trials, the stability boundary was defined by an 8-sided polygon outlining a participant's feet. Two time-to-boundary measures were determined as the absolute minimum (min Ttb) and 5th percentile from a cumulative distribution function (5th Ttb). A fractal measure derived from detrended fluctuation analysis (DFA exponent) was also calculated. DFA exponent measured long-range dependence (persistence or anti-persistence) of the COP time series (Delignières et al. 2003); it has been reported as being more sensitive than traditional measures to age-related changes thought to affect balance (Norris et al. 2005). An additional measure was obtained from the instantaneous scalar distance between COP and COM. Use of this difference measure (i.e. COP minus COM) has been suggested as a way to overcome limitations experienced when using COP- or COM-based measures separately to assess postural control (Corriveau et al. 2001). Here, the within trial RMS of COP minus COM (COP − COM) was calculated. Ankle muscle stiffness was estimated using a direct estimation method (Winter et al. 2001). Except for ellipse area and Ttb, all other measures were determined in both the antero-posterior (AP) and medial-lateral (ML) directions.

Statistical analysis

Given that the original set of dependent measures was fairly large (11), an initial variable reduction procedure was performed. Pearson correlation coefficients (r) were computed for all pairs of dependent measures using all the data obtained (Table 1). Strong correlations ($|r| \geq 0.8$) were found between the following pairs: MV_{ML} and MV_{AP}, min Ttb and 5th Ttb, COP–COM_{ML} and COP–COM_{AP}, $stiffness_{ML}$ and $stiffness_{AP}$, COP–COM_{ML} and MV_{ML}, COP–COM_{ML} and MV_{AP}, COP–COM_{AP} and MV_{ML}, and COP–COM_{AP} and MV_{AP}. Results of the statistical analyses described below were essentially the same in the AP and ML directions for MV, COP–COM, and stiffness. Considering that fatigue was induced primarily in the sagittal plane movers, ML measures for these three measures were removed. Min Ttb was also removed, because 5th Ttb was considered less sensitive to noise than min Ttb. Although MV_{AP} and COP–COM_{AP} were strongly correlated, these two measures represent different features of postural control system and they were both kept. As a result, seven dependent measures were maintained for subsequent analyses.

Preliminary investigation indicated that some dependent measures exhibited delayed responses to LMF, with peak post-fatigue values occurring at 2 or 4 min following exercise termination for some measures. Hence, the first three post-fatigue trials were included along with the three pre-fatigue trials to assess the acute effects of LMF. Three-way mixed-factor ANOVAs were performed on each dependent measure to determine the main and interactive effects of LMF (pre vs. post), joint (ankle, knee, lower back, and shoulder), and age (younger: Y vs. older: O). Tukey's Honestly Significant Difference (HSD) tests were used for post hoc comparisons whenever necessary. The level of significance was set at $P < 0.01$ for ANOVA tests (as a compromise between experiment-wise Type I error and power) and $P < 0.05$ for HSD tests.

To investigate the recovery of postural control following fatigue, a three-way mixed-factor ANOVA was first used, with independent variables of age (Y vs. O), joint (ankle and lower back), and recovery time (nine levels: 0.75–20 min). Only the data from the ankle and lower back were examined, since acute LMF effects were only evident for these two joints (see "Results"). MV_{AP} was used as the dependent measure, since previous studies suggest that it is the most reliable and sensitive COP-based measure (Prieto

Table 1 Pearson correlation coefficients among all pairs of dependent measures (all correlations were significant, at $P < 0.05$)

	EA	MV_{ML}	MV_{AP}	min Ttb	5th Ttb	DFA_{ML}	DFA_{AP}	COP–COM_{ML}	COP–COM_{AP}	$Stiffness_{ML}$
MV_{ML}	0.52									
MV_{AP}	0.54	0.93[a]								
minTtb	−0.40	−0.67	−0.61							
5th Ttb	−0.41	−0.75	−0.68	0.88[a]						
DFA_{ML}	0.03	−0.73	−0.63	0.56	0.65					
DFA_{AP}	0.15	−0.58	−0.64	0.43	0.52	0.68				
COP–COM_{ML}	0.58	0.97[a]	0.90[a]	−0.72	−0.79	−0.68	−0.53			
COP–COM_{AP}	0.59	0.88[a]	0.97[a]	−0.62	−0.69	−0.57	−0.59	0.88[a]		
$Stiffness_{ML}$	0.26	0.45	0.49	−0.38	−0.40	−0.37	−0.30	0.46	0.51	
$Stiffness_{AP}$	0.26	0.38	0.45	−0.33	−0.34	−0.24	−0.30	0.38	0.48	0.94[a]

[a] Strong correlation, $|r| \geq 0.8$

Table 2 Summary of ANOVA results (*P* values), for the effects of fatigue (*F*), joint (*J*), and age (*A*) on several measures of postural control

Parameters	Fatigue	Joint	Age	$F \times J$	$F \times A$	$J \times A$	$F \times J \times A$
EA	<0.0001*	<0.011	0.641	<0.0001*	0.033	0.783	0.240
MV_{AP}	<0.0001*	<0.0001*	0.054	<0.0001*	0.0004*	0.592	0.350
5th Ttb	<0.0001*	0.001*	0.025	0.005*	<0.0001*	0.052	0.084
DFA_{ML}	0.003*	0.2999	0.002*	0.291	0.005*	0.017	0.093
DFA_{AP}	0.109	0.1621	0.007*	0.09	0.150	0.952	0.226
COP–COM_{AP}	<0.0001*	<0.0001*	0.043	<0.0001*	0.0001*	0.885	0.471
$Stiffness_{AP}$	0.434	0.236	0.101	0.262	0.267	0.094	0.847

* Significant effect ($P < 0.01$)

et al. 1996; Corriveau et al. 2001; Lafond et al. 2004; Hertel et al. 2006; Lin et al. 2008). Post-fatigue values of MV_{AP} were normalized by the mean of the three pre-fatigue trials, thereby reflecting changes with respect to the pre-fatigue state. Except for recovery time × age, no other interaction effects were significant (see "Results"). Thus, follow-up analyses were performed for each age group separately. A significant main effect of recovery time was followed up with one-sample *t*-tests to determine at which times post-fatigue values of MV_{AP} were significantly different from the pre-fatigue value (i.e. significantly different from 1). Inspection of the post-fatigue data indicated an exponential relationship between recovery time and post-fatigue values of (normalized) MV_{AP} (see Fig. 3). Thus, nonlinear regression analyses were performed using an exponential model of the form $y = b_0 + b_1 e^{-\lambda t}$, where λ represents recovery rate (min^{-1}). The recovery rates of the two age groups were compared using a two-sample *t*-test. The level of significance was set at $P < 0.05$ for all statistical tests on recovery data.

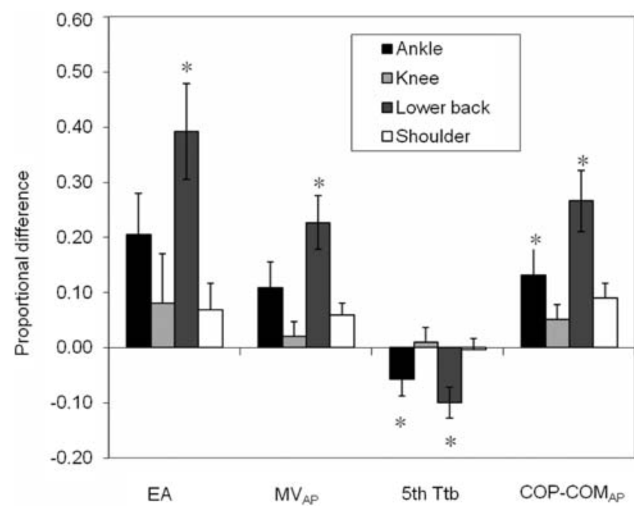

Fig. 1 Interactive effects of fatigue and joint on several measures of postural control. Values are means (SE) of the proportional differences between post-fatigue and pre-fatigue measures, and the symbol *significant ($P < 0.05$) fatigue effect

Results

Acute Effects of LMF

Main effects of LMF were the most consistent across the dependent measures, compared to other main effects and interactions (see Table 2 for a summary of ANOVA results). LMF significantly increased EA (11.9%), MV_{AP} (6.9%) and COP–COM_{AP} (10.6%), and decreased 5th Ttb (5.6%) and DFA_{ML} (1.0%). Compared to the younger group, the older group demonstrated significantly lower DFA_{ML} (7.5%) and DFA_{AP} (5.7%). The older group also had higher MV_{AP} (47.6%) and COP–COM_{AP} (36.2%), and lower 5th Ttb (22.5%), but age effects on these measures were not significant. While significant main effects of joint were found for several measures, these do not have an obvious interpretation (in contrast to interaction effects which are summarized below).

Significant LMF × joint interaction effects were found on EA, MV_{AP}, 5th Ttb, and COP–COM_{AP} (Fig. 1). Decomposing this interaction into its simple effects indicated that there was no difference between joints in the pre-fatigue condition, but that significant differences existed between joints in the post-fatigue condition (i.e. a differential effect of LMF occurred between joints). The most substantial effects of LMF were evident at the lower back, with a 39.2% increase in EA, a 22.7% increase in MV_{AP}, a 26.6% increase in COP-COM_{AP}, and a 10.0% decrease in 5^{th} Ttb. LMF at the ankle resulted in a 5.6% decrease in 5th Ttb and a 13.1% increase in COP–COM_{AP}. No significant effects of knee or shoulder LMF were evident.

Significant interaction effects of LMF × age were found for MV_{AP}, 5^{th} Ttb, DFA_{ML}, and COP–COM_{AP} (Fig. 2). For the younger group, LMF significantly increased MV_{AP} (18.6%) and COP–COM_{AP} (22.0%), and decreased 5^{th} Ttb (8.6%) and DFA_{ML} (1.7%). In contrast, no significant effects of LMF were found among the older group. The older group showed significantly larger MV_{AP} and COP–COM_{AP}, and lower 5^{th} Ttb and DFA_{ML} in both pre- and post-fatigue conditions. No significant joint × age or second-order interaction effects were found.

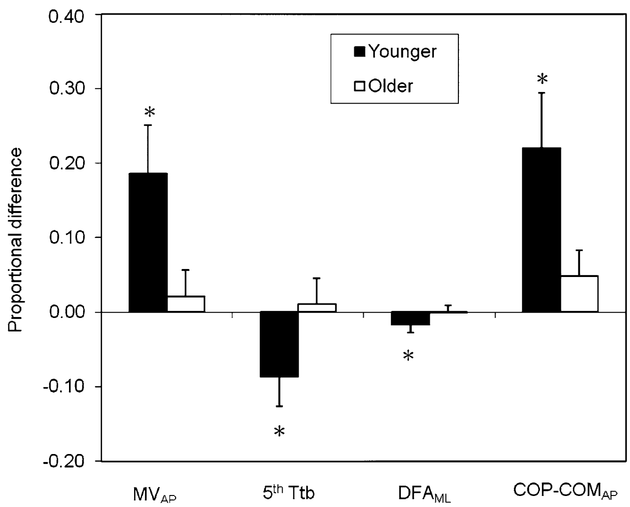

Fig. 2 Interactive effects of fatigue and age on several measures of postural control. Values are means (SE) of the proportional differences between post-fatigue and pre-fatigue measures, and the symbol *significant ($P < 0.05$) fatigue effect

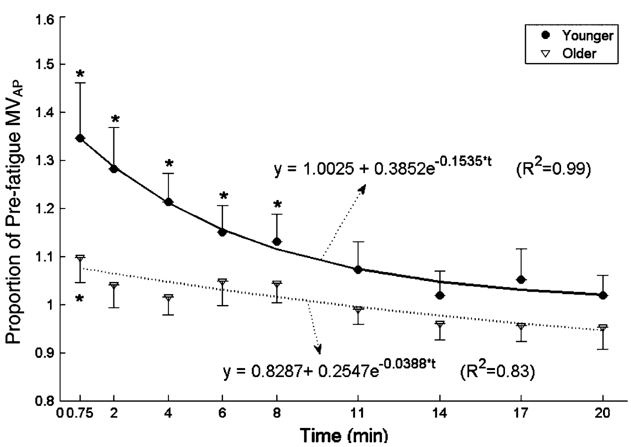

Fig. 3 Recovery of mean velocity AP (expressed as a proportion of pre-fatigue values), averaged across participants and two joints (ankle and lower back). *Error bars* indicate standard errors, and * indicates that the post-fatigue value is significantly different than the pre-fatigue value ($p < 0.05$)

Recovery of postural control

Significant ($P < 0.0001$) main effects of recovery time and joint were found on MV_{AP} during the 20 min of recovery. There was neither a significant main effect of age ($P = 0.16$) nor interactive effects of recovery time × joint ($P = 0.17$), joint × age ($P = 0.66$), or recovery time × joint × age ($P = 0.85$). The effect of recovery time × age was significant ($P = 0.001$), indicating that the temporal pattern of recovery of postural control differed between the two age groups (Fig. 3). The younger and older groups took approximately 11 and 2 min, respectively, to return to the pre-fatigue state. A significantly ($P < 0.0001$) higher rate of recovery was evident in the younger group versus the older group, with mean (SE) values of $\lambda = 0.154$ (0.024) and 0.039 (0.072) min^{-1}, respectively.

Discussion

The present study aimed to determine whether the effects of LMF on postural control differ among four muscle groups (ankle plantar flexors, knee extensors, lumbar extensors, and shoulder flexors) and also whether there were age-related differences in these effects. One of the main findings was a differential effect of LMF between the four joints. LMF at the lower back had the most substantial effects on postural control, followed by LMF at the ankle. LMF at the knee and the shoulder, in contrast, had no apparent effects. The second main finding was that these changes in postural control following LMF differed between two age groups. Immediately after the fatiguing exercises, only the younger group demonstrated impaired postural control. The younger group also exhibited a longer recovery time and a higher recovery rate. A diverse set of dependent measures was used to capture different aspects of postural control. Generally, the results of acute LMF effects were consistent across all dependent measures except for stiffness, and this is assumed in the following discussion. However, there were some discrepancies, suggesting that the main and interactive effects discussed may be different depending on what aspects of postural control are measured, and also that different measures may have differing levels of sensitivity.

The main effect of LMF found here is consistent with a number of previous studies using a variety of protocols (e.g. Lundin et al. 1993; Johnston et al. 1998; Vuillerme et al. 2001; Yaggie and McGregor 2002; Corbeil et al. 2003; Davidson et al. 2004; Pline et al. 2006). Although the mechanisms by which LMF influences postural control have not been fully elucidated, a likely contribution is the altered proprioception induced by LMF (Lundin et al. 1993; Kwon et al. 1998; Johnston et al. 1998). Indeed, several studies have demonstrated that muscle fatigue can impair joint proprioception (Voight et al. 1996; Lattanzio et al. 1997; Pedersen et al. 1999; Taimela et al. 1999). It has been suggested that impaired proprioception can delay stabilizing muscle activation, leading to decrements in postural control (Davidson et al. 2004).

It is difficult to determine the exact mechanism(s) responsible for differential effects of LMF across joints, and specifically why the most substantial effects were observed following lower back LMF. LMF at the lower back may have impaired proprioception not only locally (i.e. at the lower back), but also more distally at the ankle. Such a dual effect is supported by existing studies. Taimela et al. (1999) reported that lumbar extensor fatigue could impair the ability to sense a change in lumbar position, while Pline et al. (2005) found that lumbar extensor fatigue could impair ankle joint motion sense. The latter authors suggested that their results were due to disrupted central processing of proprioceptive signals induced by lumber extensor fatigue. Another contributing factor is the specific fatigue protocol used in this study. LMF of the lower back was induced bilaterally, while LMF of the other three joints was only induced unilaterally to the dominant side. It is likely that bilateral LMF at the other three joints would have had more substantial effects than those reported here. The larger cross-sectional areas of the lumbar extensors, compared to the muscles involved at the other joints tested, may also have contributed to the greater effects of LMF at the lower back (Vuillerme et al. 2007).

Contradictory findings exist in the literature regarding the differential effects of LMF at the ankle and knee on postural control. Kwon et al. (1998) found that LMF at the ankle had a greater effect on balance ability during unipedal stance. In contrast, Gribble and Hertel (2004a) reported that fatigue at the knee caused greater postural sway than fatigue at the ankle during unipedal stance. Bellew and Fenter (2006) examined the effects of muscle fatigue at the ankle and knee on balance using three different clinical tests. Their results indicated that postural control, as measured using the lower-extremity reach test, decreased significantly only after knee fatigue, while postural control measured with the single-limb stance time test was significantly reduced only after ankle fatigue. In the present study, ankle fatigue was found to have a greater effect than knee fatigue, consistent with Kwon et al. (1998). One reason that may contribute to such different effects is that the knee movement plays a minor role in postural control during quiet upright stance, during which either an ankle or hip strategy or a combination of both dominates postural control for both younger and older individuals (Winter et al. 1996; Gatev et al. 1999; Amiridis et al. 2003). From this point of view, it seems reasonable that fatigue at the ankle had a greater effect than fatigue at the knee.

Results of the present study indicated that LMF at the shoulder had no effect on postural control. This finding is contradictory to that of Nussbaum (2003), who reported increased postural sway with shoulder LMF. These different findings are likely due to the use of different fatigue protocols. In the earlier study, LMF at the shoulder was induced through performance of a repetitive overhead manual task. This task required neck extension, which likely induced neck muscle fatigue, and increased postural sway following neck muscle fatigue has been observed in several studies (Schieppati et al. 2003; Gosselin et al. 2004; Vuillerme et al. 2005). A higher level of central fatigue may also have occurred in the earlier study, given the more prolonged nature of the protocol.

Although a number of studies have demonstrated a decline in postural control with advancing age (e.g. Maki et al. 1990; Baloh et al. 1995; Prieto et al. 1996; Du Pasquier et al. 2003; Norris et al. 2005), none to our knowledge has investigated whether there are interactive effects of LMF and age. Our results showed that LMF-induced changes in postural control differed between younger and older groups, with only the former demonstrating impairments in posture control immediately after fatiguing dynamic exercises. Several sources for this difference can be posited. First, the older group in this study may have employed a hip strategy more efficiently in order to compensate for perturbations induced by muscle fatigue, since the hip muscles were not (or minimally) fatigued. Previous studies have indicated that older individuals rely more on a hip strategy to adapt to increased postural control demands, such as when the base of support is narrowed (Amiridis et al. 2003) or in recovery from sudden deceleration of the standing surface (Okada et al. 2001). Second, the older group may have relied more on vestibular information, although our protocols cannot provide any supporting evidence. Third, the older group may have experienced less fatigue, either in absolute or relative terms. While the fatigue protocol employed was assumed to fatigue participants to the same level, differences in motivation, tolerance for discomfort, or central fatigue may have existed.

Substantially higher post-fatigue recovery rates were found among the younger participants, which may be related to age-related differences in the recovery of muscle function and contractile properties. For example, Klein et al. (1988) showed that after fatiguing contractions older muscle exhibits a slower return to resting levels of the rate and time course of twitch relaxation. Hara et al. (1998) reported that older individuals had slower recovery of muscle fiber conduction velocity after fatigue and suggested this was related to a higher proportion of type I fibers and a reduced potential to recover membrane potential propagation and metabolic capacity.

The present results also indicated that the younger group took longer for postural control measures to return to a pre-fatigue state than the older (11 vs. 2 min). Recovery time for the younger group found here is similar to other studies, though different fatigue protocols and measures of postural control were employed. Specifically, Yaggie and McGregor (2002) reported that it took up to 20 min to recover from ankle fatigue, and Pline et al. (2006) found that recovery from lumbar extensor fatigue took 15 and 9 min for mean and peak sway velocity, respectively. The longer recovery time among the younger group likely contributed to the larger changes in postural control measures observed immediately following fatigue (i.e. 45 s following cessation of exercise).

As noted above, the fatigue protocol employed in this study was intended to fatigue each participant to the same relative level (60% of their pre-fatigue MVICs). One may argue that the differential LMF effects found here were due, at least in part, to different absolute reductions in muscle strength among the four joints and two age groups. To address this, a secondary analysis was performed: a MANOVA with MVIC as a covariate. No significant MVIC effect was found for any of the postural control measures. Several existing studies also support that muscle strength is not a confounding factor. In Tropp's (1986) study, no correlation was found between postural sway amplitude and ankle joint pronator muscle strength, and Lentell et al. (1990) found that maximum inversion and eversion moments were not correlated with unilateral postural sway amplitude. Lundin et al. (1993) reported increased unilateral postural sway after LMF at the ankle, and suggested that a reduction in muscle force was not a contributing factor, since muscle forces required to maintain postural control are relatively small compared to the maximum force-generating capability of the involved muscles.

Another potential concern is different exercise durations (endurance times) between joints and age groups. To address this issue, we performed a two-way ANOVA to assess whether endurance time differed among the four joints and two age groups. The results indicated comparable endurance times between the two age groups. The shoulder and ankle had significant longer endurance times than the other two joints. Although the longest endurance time was found for the shoulder, LMF at the shoulder had no effect on postural control. However, the lower back had the shortest endurance time, but showed the most substantial effects on postural control. Thus, it can be argued that of the duration of fatiguing exercise was unlikely to be a substantial confounding factor in the current study.

One methodological issue warrants discussion. We used unilateral fatigue of the limbs, since we expected this to be more common occupationally and in daily life (i.e. that there would be uneven levels of fatigue, and that it would be unlikely that both limbs would be fatigued equally). It seems also unlikely that both limbs would be equally fatigued using a bilateral fatiguing protocol. While there is extensive existing evidence on the effects of bilateral limb fatigue, the current study appears to provide the first indication of an effect of unilateral fatigue on bilateral postural control.

The results of this study have several practical implications. Differential effects of LMF between joints imply that some specific tasks may lead to a higher falling risk than others. For example, tasks requiring substantial levels of lumbar extension effort may be more risky than those involving primarily the shoulder musculature. No effect of LMF on postural control was evident among the older participants, suggesting that muscle fatigue, at least the level investigated here, may not be a major contributing risk factor among older workers. The lower recovery rates found among the older group, however, suggests that control strategies might benefit by providing older workers with longer rest breaks versus younger workers. These implications, together with other available evidence, can facilitate future development of strategies to mitigate the effects of LMF on postural control and to reduce occupational falls related to fatigue-induced loss of balance.

In conclusion, the effects of LMF on postural control differed among both joints and age groups. LMF of the lumbar extensors was found to cause the most substantial impairment, followed by (unilateral) ankle fatigue. Effects of LMF were modified by age, with more substantial effects evident among the younger participants. Recovery rates following LMF were also substantially higher in the younger group. Further work is needed to determine the underlying mechanisms responsible for the differential effects of LMF among joints and age groups. Postural control was assessed during quiet stance in this study, and it will be of interest to determine whether similar differential effects of LMF exist in more ecologically valid dynamic situations.

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References

Allum JHJ, Bloem BR, Carpenter MG, Hulliger M, Hadders-Algra M (1998) Proprioceptive control of posture: a review of new concepts. Gait Posture 8:214–242. doi:10.1016/S0966-6362(98)00027-7

Amiridis IG, Hatzitaki V, Arabatzi F (2003) Age-induced modifications of static postural control in humans. Neurosci Lett 350:137–140. doi:10.1016/S0304-3940(03)00878-4

Baloh RW, Spain S, Socotch TM, Jacobson K, Bell T (1995) Posturography and balance problems in older people. J Am Geriatr Soc 43:638–644

Bellew JW, Fenter PC (2006) Control of balance differs after knee or ankle fatigue in older women. Arch Phys Med Rehabil 87:1486–1489. doi:10.1016/j.apmr.2006.08.020

Berg WP, Alessio HM, Mills EM, Tong C (1997) Circumstances and consequences of falls in independent community-dwelling older adults. Age Ageing 26:261–268. doi:10.1093/ageing/26.4.261

Bergland A, Wyller TB (2004) Risk factors for serious fall related injury in elderly women living at home. Inj Prev 10:308–313. doi:10.1136/ip.2003.004721

Bilodeau M, Henderson TK, Nolta BW, Pursley PJ, Sandfort GL (2001) Effects of aging on fatigue characteristics of elbow flexor muscles during sustained submaximal contraction. J Appl Physiol 91:2654–2664

BLS (2007a) Number of nonfatal occupational injuries and illnesses involving days away from work by event or exposure leading to injury or illness and industry sector, 2006. US Department of Labor. Bureau of Labor Statistics, Washington, DC

BLS (2007b) Census of fatal occupational injuries charts, 1992–2006. US Department of Labor, Bureau of Labor Statistics, Washington, DC

Corbeil P, Blouin J, Bégin F, Nougier V, Teasdale N (2003) Perturbation of the postural control system induced by muscular fatigue. Gait Posture 18:92–100. doi:10.1016/S0966-6362(02)00198-4

Corriveau H, Hébert R, Prince F, Raîche M (2001) Postural control in the elderly: an analysis of test–retest and interrater reliability of the COP–COM variable. Arch Phys Med Rehabil 82:80–85. doi:10.1053/apmr.2001.18678

Davidson BS, Madigan ML, Nussbaum MA (2004) Effects of lumbar extensor fatigue and fatigue rate on postural sway. Eur J Appl Physiol 93:183–189. doi:10.1007/s00421-004-1195-1

de Leva P (1996) Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech 29:1223–1230. doi:10.1016/0021-9290(95)00178-6

Delignières D, Deschamps T, Legros A, Caillou N (2003) A methodological note on nonlinear time series analysis: is the open- and closed-loop model of Collins and De Luca (1993) a statistical artifact? J Mot Behav 35:86–96

Du Pasquier RA, Blanc Y, Sinnreich M, Landis T, Burkhard P, Vingerhoets F (2003) The effect of aging on postural stability: a cross sectional and longitudinal study. Clin Neurophysiol 33:213–218. doi:10.1016/j.neucli.2003.09.001

Fernie GR, Gryfe CI, Holliday PJ, Llewellyn A (1982) The relationship of postural sway in standing to the incidence of falls in geriatric subjects. Age Ageing 11:11–16. doi:10.1093/ageing/11.1.11

Gatev P, Thomas S, Kepple T, Hallett M (1999) Feedforward ankle strategy of balance during quiet stance in adults. J Physiol 514:915–928. doi:10.1111/j.1469-7793.1999.915ad.x

Gosselin G, Rassoulian H, Brown I (2004) Effects of neck extensor muscles fatigue on balance. Clin Biomech (Bristol, Avon) 19:473–479. doi:10.1016/j.clinbiomech.2004.02.001

Gribble PA, Hertel J (2004a) Effect of Lower-extremity muscle fatigue on postural control. Arch Phys Med Rehabil 85:589–592. doi:10.1016/j.apmr.2003.06.031

Gribble PA, Hertel J (2004b) Effect of hip and ankle muscle fatigue on unipedal postural control. J Electromyogr Kinesiol 14:641–646. doi:10.1016/j.jelekin.2004.05.001

Hara Y, Findley TW, Sugimoto A, Hanayam K (1998) Muscle fiber conduction velocity (MFVC) after fatigue in elderly subjects. Electromyogr Clin Neurophysiol 38:427–435

Hertel J, Olmsted-Kramer LC, Challis JH (2006) Time-to-boundary measures of postural control during single leg quiet standing. J Appl Biomech 22:67–73

Horak FB (2006) Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age Ageing 35(suppl 2):ii7–ii11

Hsiao H, Simeonov P (2001) Preventing falls from roofs: a critical review. Ergonomics 44:537–561. doi:10.1080/00140130110034480

Johnston RB, Howard ME, Cawley PW, Losse GM (1998) Effect of lower extremity muscular fatigue on motor control performance. Med Sci Sports Exerc 30:1703–1707. doi:10.1097/00005768-199812000-00008

Klein C, Cunningham DA, Paterson DH, Taylor AW (1988) Fatigue and recovery contractile properties of young and elderly men. Eur J Appl Physiol 57:684–690. doi:10.1007/BF01075989

Kwon O, Choi H, Yi C, Kwon H (1998) The effects of knee and ankle muscles surrounding the knee and ankle joints on one-leg static standing balance. J Phys Ther Sci 10:7–12. doi:10.1589/jpts.10.7

Lafond D, Corriveau H, Hébert R, Prince F (2004) Intrasession reliability of the center of pressure measures of postural steadiness in healthy elderly people. Arch Phys Med Rehabil 85:896–901. doi:10.1016/j.apmr.2003.08.089

Lanza IR, Russ DW, Kent-Braun JA (2004) Age-related enhancement of fatigue resistance is evident in men during both isometric and dynamic tasks. J Appl Physiol 97:967–975. doi:10.1152/japplphysiol.01351.2003

Lattanzio P, Petrella RJ, Sproule JR, Fowler PJ (1997) Effects of fatigue on knee proprioception. Clin J Sport Med 7:22–27

Lentell GL, Katzman LL, Walters MR (1990) The relationship between muscle function and ankle stability. J Orthop Sports Phys Ther 11:605–611

Lichtenstein MJ, Shields SL, Shiavi RG, Burger MC (1988) Clinical determinants of biomechanics platform measures of balance in aged women. J Am Geriatr Soc 36:996–1002

Lin D, Seol H, Nussbaum MA, Madigan ML (2008) Reliability of COP-based postural sway measures and age-related differences. Gait Posture 28:337–342. doi:10.1016/j.gaitpost.2008.01.005

Lundin TM, Feuerback JW, Grabiner MD (1993) Effect of plantar flexor and dorsiflexor fatigue on unilateral postural control. J Appl Biomech 9:191–201

Mackey DC, Robinovitch SN (2005) Postural steadiness during quiet stance does not associate with ability to recover balance in older women. Clin Biomech (Bristol, Avon) 20:776–783. doi:10.1016/j.clinbiomech.2005.05.002

Mademli L, Arampatzis A, Karamanidis K (2008) Dynamic stability control in forward falls: postural corrections after muscle fatigue in young and older adults. Eur J Appl Physiol 103:295–306. doi:10.1007/s00421-008-0704-z

Maki BE, Holliday PJ, Fernie GR (1990) Aging and postural control. A comparison of spontaneous- and induced-sway balance tests. J Am Geriatr Soc 38:1–9

Merletti R, Farina D, Gazzoni M, Schieroni MP (2002) Effect of age on muscle functions investigated with surface electromyography. Muscle Nerve 25:65–76. doi:10.1002/mus.10014

Norris JA, Marsh AP, Smith IJ, Kohut RI, Miller ME (2005) Ability of static and statistical mechanics posturographic measures to distinguish between age and fall risk. J Biomech 38:1263–1272. doi:10.1016/j.jbiomech.2004.06.014

Nussbaum M (2003) Postural stability is compromised by fatiguing overhead work. Am Ind Hyg Assoc J 64:56–61

Ochsendorf DT, Mattacola CG, Arnold BL (2000) Effect of orthotics on postural sway after fatigue of the plantar flexors and dorsiflexors. J Athl Train 35:26–30

Okada S, Hirakawa K, Takada Y, Kinoshita H (2001) Age-related differences in postural control in humans in response to a sudden deceleration generated by postural disturbance. Eur J Appl Physiol 85:10–18. doi:10.1007/s004210100423

Owings TM, Pavol MJ, Foley KT, Grabiner MD (2000) Measures of postural stability are not predictors of recovery from large postural disturbances in healthy older adults. J Am Geriatr Soc 48:42–50

Pajala S, Era P, Koskenvuo M, Kaprio J, Törmäkangas T, Rantanen T (2008) Force platform balance measures as predictors of indoor and outdoor falls in community-dwelling women aged 63–76 years. J Gerontol A Biol Sci Med Sci 63:171–178

Pedersen J, Lönn J, Hellström F, Djupsjöbacka M, Johansson H (1999) Localized muscle fatigue decreases the acuity of the movement sense in the human shoulder. Med Sci Sports Exerc 31:1047–1052. doi:10.1097/00005768-199907000-00019

Pline KM, Madigan ML, Nussbaum MA, Grange RW (2005) Lumber extensor fatigue and circumferential ankle pressure impair ankle joint motion sense. Neurosci Lett 390:9–14. doi:10.1016/j.neulet.2005.07.047

Pline KM, Madigan ML, Nussbaum MA (2006) Influence of fatigue time and level on increases in postural sway. Ergonomics 49:1639–1648. doi:10.1080/00140130600901678
Prieto TE, Myklebust JB, Hoffmann RG, Lovett EG, Myklebust BM (1996) Measures of postural steadiness: differences between healthy young and elderly adults. IEEE Trans Biomed Eng 43:956–966. doi:10.1109/10.532130
Punakallio A (2005) Balance abilities of workers in physically demanding jobs: with special reference to firefighters of different ages. J Sports Sci Med 4(Suppl. 8):1–47
Rubenstein L (2006) Falls in older people: epidemiology, risk factors and strategies for prevention. Age Aging 35(suppl 2):ii37–ii41
Salavati M, Moghadam M, Ebrahimi I, Arab AM (2007) Changes in postural stability with fatigue of lower extremity frontal and sagittal plane movers. Gait Posture 26:214–218. doi:10.1016/j.gaitpost.2006.09.001
Schieppati M, Nardone A, Schimid M (2003) Neck muscle fatigue affects postural control in man. Neuroscience 121:277–285. doi:10.1016/S0306-4522(03)00439-1
Stel VS, Smit JH, Pluijm SMF, Lips P (2003) Balance and mobility performance as treatable risk factors for recurrent falling in older persons. J Clin Epidemiol 56:659–668. doi:10.1016/S0895-4356(03)00082-9
Taimela S, Kankaanpää M, Luoto S (1999) The effect of lumbar fatigue on the ability to sense a change in lumbar position. Spine 24:1322–1327. doi:10.1097/00007632-199907010-00009
Toossi M (2005) Labor force projections to 2014: retiring boomers. Mon Labor Rev 128:25–44
Tropp H (1986) Pronator muscle weakness in functional instability of the ankle joint. Int J Sports Med 7:291–294. doi:10.1055/s-2008-1025777
van Wegen EEH, van Emmerik REA, Riccio GE (2002) Postural orientation: age-related changes in variability and time-to-boundary. Hum Mov Sci 21:61–84. doi:10.1016/S0167-9457(02)00077-5
Voight ML, Hardin JA, Blackburn TA, Tippett S, Canner GC (1996) The effects of muscle fatigue on and the relationship of arm dominance to shoulder proprioception. J Orthop Sports Phys Ther 23:348–352
Vuillerme N, Nougier V, Prieur J (2001) Can vision compensate for a lower limbs muscular fatigue for controlling posture in humans? Neurosci Lett 308:103–106. doi:10.1016/S0304-3940(01)01987-5
Vuillerme N, Pinsault N, Vaillant J (2005) Postural control during quiet standing following cervical muscular fatigue: effects of changes in sensory inputs. Neurosci Lett 378:135–139. doi:10.1016/j.neulet.2004.12.024
Vuillerme N, Anziani B, Rougier P (2007) Trunk extensor muscles fatigue affects undisturbed postural control in young healthy adults. Clin Biomech (Bristol, Avon) 22:489–494. doi:10.1016/j.clinbiomech.2007.01.007
Winter DA (2004) Biomechanics and motor control of human movement, 3rd edn. Wiley, New Jersey
Winter DA, Prince F, Frank JS, Powell C, Zabjek KF (1996) Unified theory regarding A/P and M/L balance in quiet stance. J Neurophysiol 75:2334–2343
Winter DA, Patla AE, Rietdyk S, Ishac MG (2001) Ankle muscle stiffness in the control of balance during quiet standing. J Neurophysiol 85:2630–2633
Yaggie JA, McGregor SJ (2002) Effects of isokinetic ankle fatigue on the maintenance of balance and postural limits. Arch Phys Med Rehabil 83:224–228. doi:10.1053/apmr.2002.28032
Yamada H, Okada M, Nemoto S, Shiozaki T, Kizuka T, Kuno S, Masuda T (2000) Effects of aging on EMG variables during fatiguing isometric contractions. J Hum Ergol (Tokyo) 29:7–14
Yassierli, Nussbaum MA (2007) Muscle fatigue during intermittent isokinetic shoulder abduction: age effects and utility of electromyographic measures. Ergonomics 50:1110–1126
Yassierli NussbaumMA, Iridiastadi H, Wojcik LA (2007) The influence of age on isometric endurance and fatigue is muscle dependent: a study of shoulder abduction and torso extension. Ergonomics 50:26–45