Long-Term Muscle Fatigue After Standing Work

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Objective: The aims of this study were to determine long-term fatigue effects in the lower limbs associated with standing work and to estimate possible age and gender influences.

Background: The progressive accumulation of muscle fatigue effects is assumed to lead to musculoskeletal disorders, as fatigue generated by sustained low-level exertions exhibits long-lasting effects. However, these effects have received little attention in the lower limbs.

Method: Fourteen men and 12 women from two different age groups simulated standing work for 5 hr including 5-min seated rest breaks and a 30-min lunch. The younger group was also tested in a control day. Muscle fatigue was quantified by electrically induced muscle twitches (muscle twitch force [MTF]), postural stability, and subjective evaluation of discomfort.

Results: MTF showed a significant fatigue effect after standing work that persisted beyond 30 min after the end of the workday. MTF was not affected on the control day. The center of pressure displacement speed increased significantly over time after standing work but was also affected on the control day. Subjective evaluations of discomfort indicated a significant increase in perception of fatigue immediately after the end of standing work; however, this perception did not persist 30 min after. Age and gender did not influence fatigue.

Conclusion: Objective measures show the long-term effects of muscle fatigue after 5 hr of standing work; however, this fatigue is no longer perceived after 30 min of rest postwork.

Application: The present results suggest that occupational activities requiring prolonged standing are likely to contribute to lower-extremity and/or back disorders.

Keywords: muscle twitch force, postural stability, discomfort, age, gender

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HUMAN FACTORS
Vol. XX, No. X, Month XXXX, pp. 1–12
DOI: 10.1177/0018720815590293

INTRODUCTION

Many workplaces require the workers to perform their tasks standing. Workers spending most of their time on their feet include retail staff, assembly line workers, and health care personnel, among others ("Standing Problem," 2005). The analysis of the European Survey of Working Conditions (Parent-Thirion et al., 2012) reveals that 47% of employees stand for more than 75% of their work time. In addition, prolonged standing at work was associated with reports of fatigue, leg muscle pain, and backache (Graf, Krieger, Läubli, & Martin, 2015). These results parallel studies investigating the association of prolonged standing at work with musculoskeletal disorders. In a recent review of health risks associated with prolonged standing, Waters and Dick (2014) presented 10 studies reporting evidence of low-back problems after standing over 50% of the work shift. Moreover, Gregory and Callaghan (2008) confirmed that individuals who stand for more than 2 hr are vulnerable to low-back pain. In a case control study, Elsner, Nienhaus, and Beck (1996) showed that prolonged standing at work was associated with knee arthrosis in women. A review by D'Souza, Franzblau, and Werner (2005) revealed that ankle/foot musculoskeletal disorders may be associated with standing work. Ryan (1989) suggested that the prevalence of ankle, foot, and lower-leg complaints in supermarket workers was higher for cashiers standing more than 90% of the work shift when compared to other employees. Standing the majority of the workday is also associated with ankle/foot musculoskeletal symptoms and plantar fasciitis (Riddle, Pulisic, Pidcoe, & Johnson, 2003).

Antifatigue mats or antifatigue shoe insoles (Orlando & King, 2004; Cham & Redfern, 2001) have been proposed as prevention methods to alleviate the consequences of prolonged standing; however, the effectiveness of both are unconfirmed as they do not seem to reduce the physiological effects of muscle fatigue (Brownie & Martin, 2015; Zander, King, & Ezenwa, 2004). From a review, Redfern and Cham (2000) concluded that although discomfort may be relieved by softer flooring conditions, objective measures of fatigue presented conflicting results. This finding was also emphasized by later studies (King, 2002; Lin, Chen, & Cho, 2012). Hence, localized muscle fatigue, which is considered as a precursor of musculoskeletal disorders (Armstrong et al., 1993; Côté, 2014; Edwards, 1988), may not be relieved by these methods (Kim, Stuart-Buttle, & Marras, 1994).

Muscle fatigue, defined as the reduction in the ability to produce force in response to a desired effort (Edwards, 1981; Enoka & Stuart, 1992; Gandevia, 2001), results from high-force and/or prolonged muscle contractions as well as low-force and/or intermittent contractions (Adamo, Khodaee, Barringer, Johnson, & Martin, 2009; Blangsted, Sjoogaard, Madeleine, Olsen, & Sogaard, 2004). The type of fatigue associated with low levels of muscle exertion, commonly named long-term fatigue, may be objectively measured by specific methods quantifying the magnitude of electrically induced muscle twitches at low frequencies (Adamo et al., 2009; Adamo, Martin, & Johnson, 2002; Edwards, Hill, Jones, & Merton, 1977) or the shift in the median or mean frequency of surface electromyography (EMG) power spectra obtained from low-level static contractions (Blangsted et al., 2004; Sogaard, Blangsted, Jorgensen, Madeleine, & Sjogaard, 2003). This type of fatigue may persist up to 24 hr after exposure (Edwards et al., 1977).

Long-term fatigue after low-force exertions activities has been investigated in the upper limbs (Adamo et al., 2002, 2009; Sogaard et al., 2003). However, the extent to which long-term fatigue develops and persists in the lower limbs after prolonged standing work has received little attention. Although postural stability (Freitas, Wieczorek, Marchetti, & Duarte, 2005; Madeleine, Voigt, & Arendt-Nielsen, 1998), EMG (Cham & Redfern, 2001; Hansen, Winkel, & Jorgensen, 1998) and subjective discomfort (Antle & Côté, 2013; Drury et al., 2008) have been used to quantify standing fatigue, most studies involved exposures ≤2 hr, and all included only immediate postwork effects. Furthermore, subjective evaluations do not appear to correlate with long-term muscle fatigue in upper-body muscles (Adamo et al., 2009; Nakata, Hagner, & Jonsson, 1992). Thus, there is a need to investigate the development of fatigue in the lower limbs during prolonged standing work and to consider possible age and gender effects, which are factors that may influence fatigue (Hunter, Critchlow, & Enoka, 2004).

Hence, we attempted to address the issue of long-term fatigue in the lower limbs during prolonged standing work by testing the following hypotheses:

1. Long-term fatigue develops in the lower-limb muscles as a consequence of prolonged standing work.
2. Age and gender influence muscle fatigue induced by standing work.
3. Muscle twitch force (MTF) and postural stability are sensitive methods to assess the long-lasting effects of fatigue, whereas subjective evaluation of discomfort is not.

METHOD

Participants

Twenty-six healthy individuals (14 men and 12 women) participated in this study as paid volunteers. The participants were recruited from two different age groups, 13 young adults (seven males and six females; 18–30 years old) and 13 older workers (seven males and six females; 50–65 years old). Participants were part of the working-age population, but having a standing job was not required. Their average height and weight (± *SD*) were 172.9 (± 12.5) cm and 67.9 (± 10.2) kg, respectively. The exclusion criteria included current pregnancy and any neurological or musculoskeletal conditions that could interfere with the study. All participants signed an informed consent form approved by the ethics committee of ETH Zürich.

Apparatus

Experimental setup (MTF). The participants were seated in a comfortable armchair with their right foot resting on a reclined, adjustable plate equipped with a strain gauge force transducer.

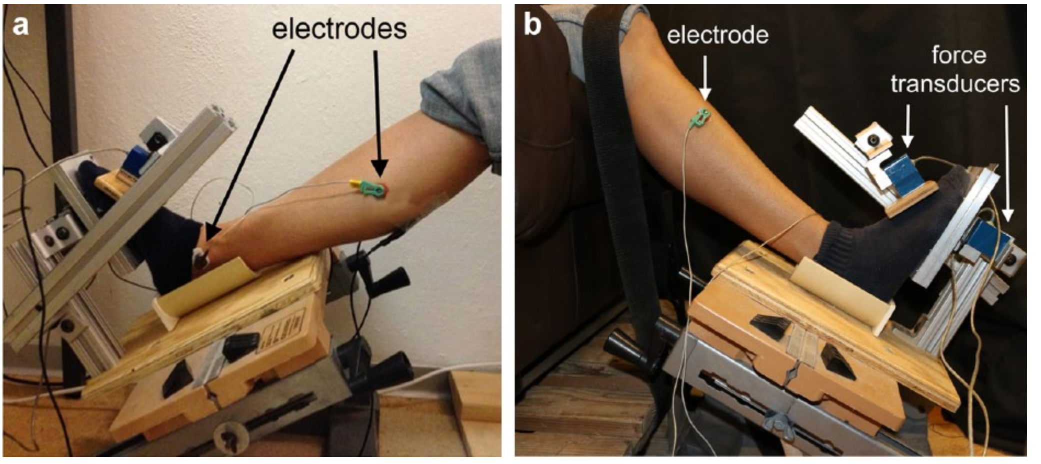

Figure 1. Experimental setup for measuring muscle twitch force elicited in the (a) gastrocnemius-soleus and (b) tibialis anterior muscles.

The plate was adjusted to obtain a right-leg posture corresponding to a knee-included angle of about 120° and ankle-included angle of 90° (Figure 1a). The right leg was stabilized with a strap passing over the knee and attached to the floor. A second plate placed over the dorsal side of the foot, also equipped with a force transducer, was attached to a fixed frame through adjustable supports. This plate contacted the foot at the midpoint between the metatarsals joints (Figure 1b). The initial contact force was set to the same value for all participants and verified for each replacement of the foot during the experiment. Both force transducers were connected to amplifiers. No voluntary effort was necessary to maintain the foot-leg posture, and required relaxation was verified using both force signals. Each transducer measured the twitch force elicited by electrical stimulation of the gastrocnemius-soleus (GS) and tibialis anterior (TA) muscles, respectively.

Electrical stimulation (MTF). Muscle stimulation and procedure were adapted from previous studies using MTF to quantify the long-term effects of fatigue (Adamo et al., 2002, 2009). Circular stimulation electrodes (Ag/AgCL, ø8 mm) filled with gel were placed on the skin over the GS and TA muscles. A disposable pre-gelled surface electrode (57 × 34 mm; Kendall) was placed on the lower area of the medial malleolus. The optimal location was determined by the area of the muscles for which a maximum twitch force was obtained in accordance to the maximum sustainable discomfort elicited by the stimulation. Electrical pulses of 1-ms duration were delivered at a frequency of 2 Hz, with a current in the range of 10 to 30 mA. Each participant indicated when the stimulation level became unpleasant, and then the intensity was adjusted to the highest level that could be tolerated for the entire stimulation period. This procedure was used to recruit the largest number of muscle fibers without inducing pain beyond a level of tolerable discomfort. The locations of the stimulation electrodes were clearly marked and measured, relative to the tibia bone and lower edge of the patella, for exact replacement on succeeding measurement days. The electrical stimulation was delivered through a stimulator (GS880) connected to an isolation unit (SIU5) and a constant current unit (CCU1A), all from Grass™ Instruments.

For each MTF measure, stimulations were applied for 3 to 4 min to reach the steady-state twitch-force level following potentiation (Desmedt & Hainaut, 1968; Rankin, Enoka, Volz, & Stuart, 1988). Three series of 30 twitches with a coefficient of variation of less than 5% were then recorded (Adamo et al., 2002, 2009). The MTF was determined as the average of the three series.

Postural stability. The participants were asked to stand still on a force plate (Kistler, Winterthur,

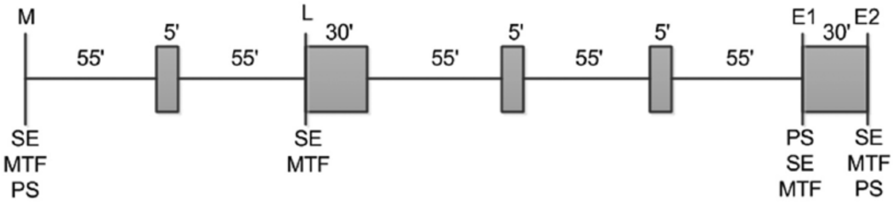

Figure 2. Experimental day timeline. Boxes represent the sitting time and horizontal segments the standing time. Subjective evaluation of discomfort-fatigue (SE), muscle twitch force (MTF), and postural stability (PS) were measured at different times (M, L, E1, E2).

Switzerland), without shoes, in an upright posture with arms at the sides for 30 s and with their eyes closed. Footprints, corresponding to shoulder width with 15° ankle abduction, were marked on the plate to obtain the same foot placement for every test. The force plate system provided the *x* and *y* coordinates of the center of pressure (COP). The COP displacement speed (Geurts, Nienhuis, & Mulder, 1993) was calculated using Matlab™.

Subjective evaluation of discomfort-fatigue. Participants assessed localized discomfort on identical 10-cm visual analogue scales (0–10) for 11 body areas (lower back; right and left hip/upper leg, knee, lower leg, ankle, foot) indicated on a body diagram (adapted Nordic questionnaire; Kuorinka et al., 1987). The participants rated each discomfort level by placing a vertical mark through the line of the corresponding scale.

Work Task

Participants simulated standing work that consisted of performing various light manual tasks on a workbench adjusted to elbow height to prevent torso flexion. The tasks included computer work, reading, and playing games, among others, freely selected by the participants and alternated to prevent boredom. Forceful exertions were excluded. To maintain consistency across conditions and over time, supporting the arms on the workbench was not allowed, and the same type of new sport shoe was provided to all participants. The participants were allowed to move freely within an area of 1.5 m² in front of the workbench on the linoleum-over-concrete laboratory floor. The standing tasks were performed over five 55-min periods. Five minutes of rest was provided at the end of the first, third, and fourth standing work period, and a 30-min lunch break was provided at the end of the second standing work period. The participants sat in a comfortable armchair during the rest periods.

Procedure

All participants were instructed to minimize physical exertions 24 hr prior to the experiment. Activities requiring a high level of physical exertion were not allowed. The total duration of the experimental day was about 7 hr. All participants were informed about the experimental procedure and signed a consent form prior to the experiment. MTF and subjective evaluation of discomfort-fatigue were performed according to the schedule illustrated in Figure 2: in the morning before the first standing work period (baseline, M), at the beginning of the lunch break (L), immediately after the last work period (E1), and 30 min after that period (E2). Postural stability was tested in M, E1, and E2. The participants remained seated during the last 30 min after the end of the work task. Lunch and drinks were brought to the participants. In addition, to contrast standing work with a seated "office" day, the younger participants were also tested on a control day during which they remained mostly seated without performing any specific task besides usual computer work. The measurement protocol was the same for both days, skipping only E2 on the control day. The order of the experimental and control day was randomized, and each was performed on 2 nonconsecutive days.

Data Analysis

Repeated-measures analysis of variance (ANOVA) was applied to each dependent variable

TABLE 1: ANOVA for GS and TA MTF and COP Speed

	MTF GS (r^2_{adj} = .73)		MTF TA (r^2_{adj} = .45)		COP Speed (r^2_{adj} = .40)	
Source	*F* Ratio	*p*	*F* Ratio	*p*	*F* Ratio	*p*
Time	36.62	**<.0001**	6.31	**.0008**	3.96	**.03**
Age	0.19	.67	1.53	.23	0.08	.78
Gender	0.48	.5	0.09	.77	0.63	.44
Age × Time	2.03	.12	1.88	.14	0.21	.81
Gender × Time	0.42	.74	0.26	.85	1.93	.16
Age × Gender × Time	0.09	.96	0.47	.70	0.12	.89

Note. GS = gastrocnemius-soleus; TA = tibialis anterior; MTF = muscle twitch force; COP = center of pressure. Bold font indicates significant values, α = .5.

(MTF and COP speed) to determine the influence of time (M, L, E1, and E2) and estimate the main effects of gender and age, and/or their interaction, on fatigue indicators on the experimental day. When main effects or interactions were significant, post hoc Tukey HSD tests were used to compare the baseline reference measures (M) with the postwork task measures (L and E1) and recovery measures (E2) and to compare postwork measures (E1 vs. E2). Significance of all tests was set at α = .05. The measures subsequent to time M were expressed in percentages of this reference. This analysis was also applied to compare the experimental and control days for the younger group. All data are expressed as means and standard errors.

Subjective responses were assumed to be normally distributed and continuous, as visual analogue scales were continuous. Hence, ANOVAs were performed using a two-step process. First, ANOVAs were performed for each body part. Then evaluations associated with a significant time effect and highly correlated were considered for grouping/combination. The Cronbach coefficient alpha (CCA) was used to explore combined scales, which were then analyzed with ANOVAs and post hoc tests. Correlations between the sizes of the change in subjective ratings and MTF, at times E1 and E2 relative to the baseline M, were also computed using Pearson's correlation.

RESULTS

ANOVA results for the GS and TA MTF and COP speed are summarized in Table 1.

MTF

GS MTF. The ANOVA (Table 1) showed a significant influence of standing work on MTF over time for the GS muscles on the experimental day. The main effects of age and gender, as well as their interactions with time, were not significant. Tukey HSD comparisons showed that GS MTF was significantly lower at E1 (*M* = 68.39%, *SE* = 5.13%; $p < .001$) and at E2 (*M* = 64.61%, *SE* = 4.99%; $p < .001$) than at baseline M (Figure 3a), and the decrease in MTF persisted at least 30 min after work as MTF was not significantly different between E1 and E2 (p = .82). In addition, measures at M and L times did not differ significantly (p = .89).

TA MTF. The ANOVA (Table 1) showed a significant influence of standing work on the MTF over time for the TA muscle on the experimental day. The main effects of age and gender, as well as their interactions with time, were not significant. Tukey HSD comparisons showed that TA MTF was significantly lower at E1 (*M* = 74.0%, *SE* = 7.1%; p = .03) and at E2 (*M* = 65.58, *SE* = 6.08%; p = .003) than at baseline M (Figure 3b), and the decrease in MTF persisted at least 30 min after work as MTF was not significantly different between E1 and E2 (p = .83). In addition, measures at M and L times did not differ significantly (p = .98).

Postural Stability

The ANOVA (Table 1) showed a significant influence of standing work on COP speed over time on the experimental day. The main effects of age and gender, as well as their interactions

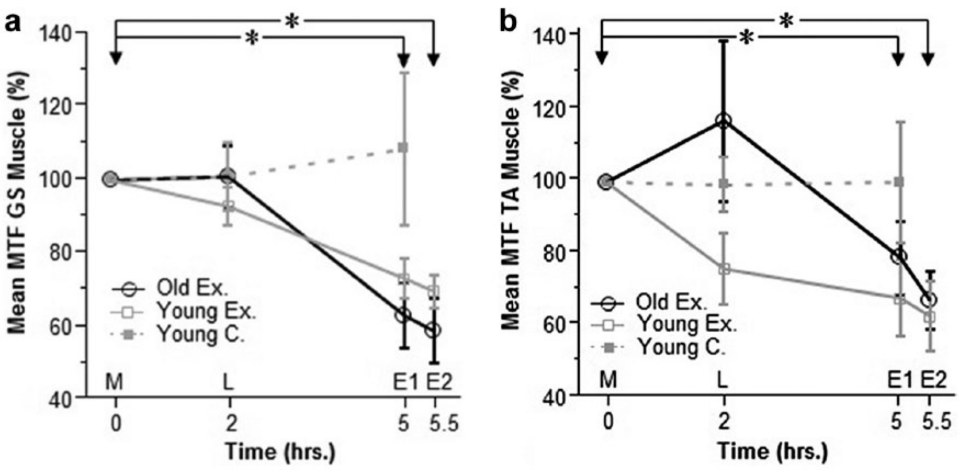

Figure 3. Changes in muscle twitch force, (a) gastrocnemius-soleus and (b) tibialis anterior, relative (%) to baseline (M). Ex. = experimental day; C. = control day. Vertical bars indicate standard errors. Asterisk (*) indicates a significant difference on the experimental day.

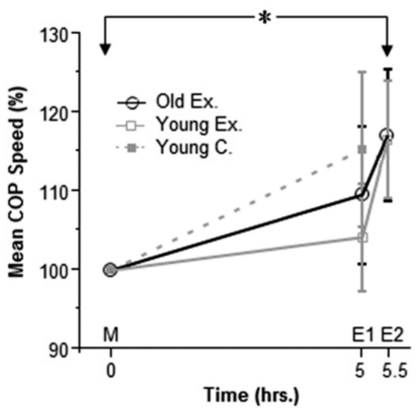

Figure 4. Changes in center-of-pressure speed were relative (%) to baseline (M). Ex. = experimental day; C. = control day. Vertical bars indicate standard errors. Asterisk (*) indicates a significant difference on the experimental day.

with time, were not significant. Tukey HSD comparisons showed that COP speed was significantly higher at E2 (M = 116.87%, SE = 5.49%; p = .02) but not at E1 (M = 106.81%, SE = 5.39%; p = .41) when compared to baseline M (Figure 4).

Subjective Evaluation of Discomfort-Fatigue

Three combined scales based on a CCA > 0.8 were created: (a) hips area ∋ low back, both hips, and upper legs; (b) knees ∋ both knees; and (c) lower legs area ∋ both lower legs, ankles, and feet. The corresponding ANOVA results are presented in Table 2.

Hips area. The ANOVA (Table 2) showed a significant influence of standing work on the subjective ratings of fatigue in the hips area. The Gender × Time interaction was significant, but the Age × Time interaction was not. Post hoc comparisons showed that discomfort was (a) significantly greater for both genders (female, p < .001; male, p = .03) immediately after standing work (E1) when compared to baseline M (Figure 5a); (b) not significantly different between females and males at times L (p = 1.0), E1 (p = .67), and E2 (p = .99); and (c) not significantly different at L (female, p = .69; male, p = .65) and E2 (female, p = .08; male, p = 1.0) when compared to baseline M for both genders.

Knees. The ANOVA (Table 2) showed a significant influence of standing work on the subjective ratings of fatigue in the knees. Neither the main effects of gender or age nor their interactions were significant. Post hoc comparisons showed that ratings were not significantly greater at time L (p = .63), but it was at E1 (p < .001) when compared to baseline M. However, the perception of discomfort did not persist postwork, as ratings were not significantly different (p = .33) between E2 and baseline M (Figure 5b).

Lower legs area. The ANOVA (Table 2) showed a significant influence of standing work

TABLE 2: ANOVA for Subjective Discomfort-Fatigue Ratings

	Hips Area (r^2_{adj} = .42)		Knees (r^2_{adj} = .66)		Lower Legs Area (r^2_{adj} = .49)	
Source	*F* Ratio	*p*	*F* Ratio	*p*	*F* Ratio	*p*
Time	15.13	**<.0001**	6.66	**.0003**	40.71	**<.0001**
Age	2.40	.13	3.13	.09	7.32	**.013**
Gender	0.61	.44	0.001	.97	0.39	.54
Age × Time	0.21	.89	1.57	.20	8.46	**<.0001**
Gender × Time	2.78	**.04**	1.29	.28	0.63	.60
Age × Gender × Time	0.71	.54	0.90	.44	1.27	.28

Note. Bold font indicates significant values, α = .5.

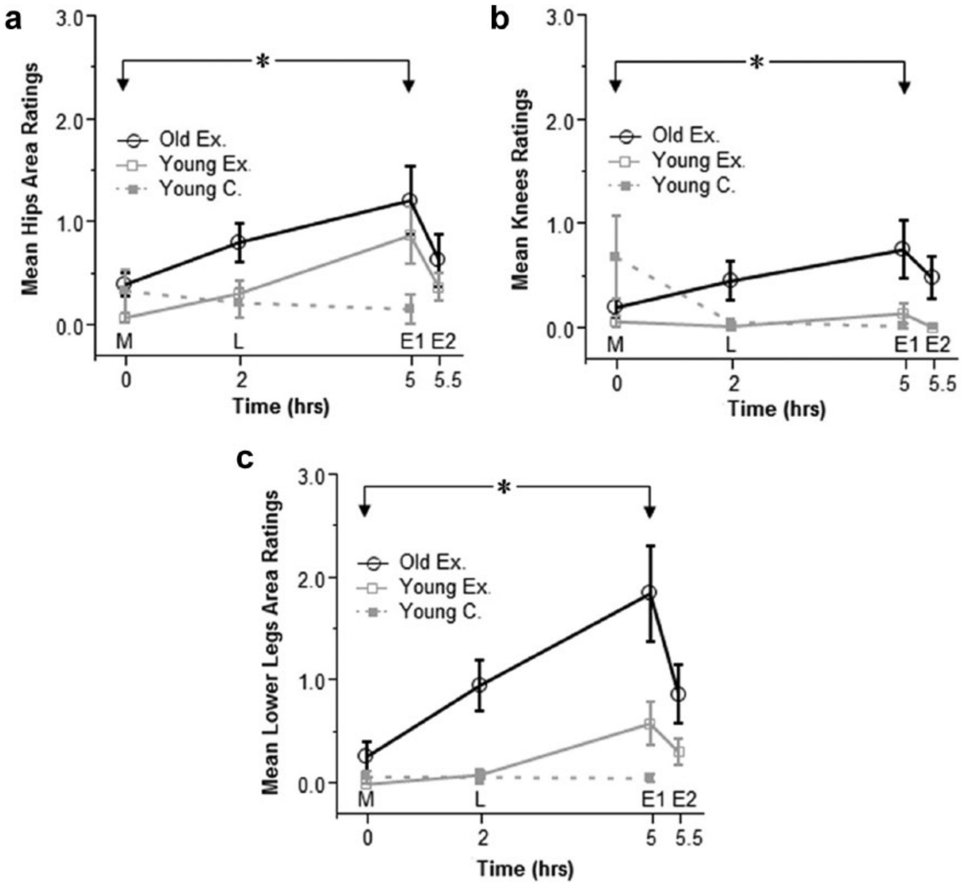

Figure 5. Changes in discomfort-fatigue ratings: (a) hips area, (b) knees, and (c) lower legs area. Ex. = experimental day; C. = control day. Vertical bars indicate standard errors. Asterisk (*) indicates a significant difference on the experimental day.

on the subjective ratings of fatigue in the lower legs area. The Age × Time interaction was significant; in contrast, the Gender × Time interaction was not significant. Post hoc comparisons showed that the perception of discomfort for the older group was significantly greater at times L ($p < .001$) and E1 ($p < .001$) but for the younger group only at E1 ($p < .001$) when compared to baseline M. Ratings were greater for the older than the younger group at time E1 ($p = .004$) but not at times L ($p = .16$) and E2 ($p = .53$). The perception of discomfort did not persist postwork for the younger group, as ratings at E2 were not significantly different from baseline M ($p = .39$). For the older group, perception of discomfort decreased significantly ($p < .001$) from E1 to E2. However, this decrease did not correspond to a complete return to baseline, as perception at E2 is still different ($p < .001$) from M (Figure 5c).

Correlation Between Subjective Evaluation and MTF

The decrease in GS and TA MTF magnitude was not correlated ($r^2_{adj} < .01$) to the increase in fatigue ratings in the lower legs area, knees, and hips area between M and E1. Similar results were found between M and E2 ($r^2_{adj} < .01$) for each fatigue rating.

Control Day (Younger Group)

The ANOVA showed that variations in GS MTF over time on the control day were not significant, $F(3, 30) = 1.28$, $p = .30$, as illustrated by Figure 3a. Neither the main effect of gender nor its interaction with time was significant. Similar outcomes were found for TA MTF. The variations in TA MTF over time were not significant, $F(3, 27) = 0.17$, $p = .91$; neither was the main effect of gender nor the interaction with time, as illustrated by Figure 3b. In addition, COP speed was not significantly different over time, $F(1, 20) = 1.90$, $p = .17$, as illustrated by Figure 4. Furthermore, ratings did not vary significantly over time for fatigue perceived in the different body areas.

DISCUSSION

In the present study we investigated the long-term effects of fatigue in the lower limbs after 5 hr of standing work including rest breaks, as is observed in manufacturing plants. Persistence of the decrease in MTF magnitude and the increase of COP displacement speed observed 30 min postwork are indicators of the long-lasting effects of muscle fatigue. Recovery 30 min postwork, indicated by most of the subjective evaluations, contrasts with the objective measure showing fatigue persistence. Hence, we assume that 5 hr of standing work has a significant impact on lower-limb fatigue, and the effect may not be perceived.

MTF and Fatigue

Authors of previous upper-limb studies noted the long-term fatigue effects of prolonged low-force contractions (Adamo et al., 2002, 2009; Blangsted et al., 2004; Johnson, Ciriello, Kerin, & Dennerlein, 2013). Fatigue effects of long duration have been associated with mechanisms taking place at the peripheral level, and they have been evidenced by electrical stimulations that bypass central influences. More specifically, the mechanism responsible for the decrease in MTF is associated with the failure in excitation-contraction coupling (Enoka & Stuart, 1992; Westerblad, Bruton, Allen, & Lännergren, 2000), which exhibits a slow recovery (Edwards et al., 1977). The present study showed that the MTF in the GS and TA muscles decreases significantly after prolonged standing and persists at least 30 min after standing work. Consistent with results obtained in the upper limbs, as mentioned earlier, the decrease in MTF indicates that prolonged low-force exertions also have detrimental effects in lower leg muscles, and the long-term effects of fatigue in the upper and lower limbs are likely to stem from the same mechanism.

As fatigue has been shown to alter motor control/movements and postural control (Paillard, 2011), as observed here and in other studies (e.g., Johnston, Howard, Cawley, & Losse, 1998), then it may be presumed that changes in posture, even subtle, resulting from fatigue effects contribute to changes in the low back-hip relationship, which in the long term may contribute to low-back disorders. This assumption is in line with the perspective that fatigue is a precursor of musculoskeletal disorders (Armstrong et al., 1993; Edwards, 1988). The perniciousness of the long-lasting effects appears to be related to a lack of their conscious perception, as indicated by the divergence of objective and subjective measures postwork.

Furthermore, the decrease in MTF occurred similarly in the GS and TA muscles despite their difference in muscle fiber composition (Johnson, Polgar, Weightman, & Appleton, 1973) and antagonistic functions. Their respective fatigue suggests that the GS and TA muscles are to some extent used similarly while performing standing work. However, the variability was greater for the TA than for the GS MTF (see Figure 3). This difference probably stems from the difficulty of the measurement associated with a delicate placement of the force transducer (in terms of orientation and location) for the TA muscle and the need to readjust the transducer for every repetition of the measure. As standing work induces swelling of the foot, then transducer adjustments were needed for each series of measurements to maintain constant its pressure over the dorsal side of the foot (Figure 1). This requirement introduced a source of variation. Therefore, since GS and TA MTF provide similar information and each measurement required significant preparation and testing time, it is advisable to use only GS MTF.

There was no evidence that fatigue had developed after 2 hr of standing work with 5 min seated rest in between. Hence, this standing work duration including the rest breaks may be acceptable, but 5 hr with the tested rest cycle may present some risk. It is expected that after a common 8-hr work shift, the long-lasting effects of fatigue from standing work will be more pronounced than found in this study. In addition, the absence of significant effects on MTF on the control day clearly supports the conclusion that long-term fatigue develops as a consequence of standing.

Although not significant, gender and age effects suggest possible tendencies of differentiation. This lack of significance may be due to the limited statistical power resulting from the modest number of subjects in the respective subgroups. However, previous studies concerning upper-limb muscles did not reveal gender or age effects on MTF (e.g., Adamo et al., 2002, 2009) from low-level repetitive exertions. Gender or age influences on muscle fatigue (Wojcik, Nussbau, Lin, Shibata, & Madigan, 2011) may result primarily from high-force exertion tasks, which are associated with different mechanisms of fatigue, as acknowledged earlier (Edwards et al., 1977; Enoka & Stuart, 1992; Johnson et al., 2013; Jones, 1996). Hence, we assume that considering gender and age as major factors may not be a priority in the evaluation of fatiguing tasks involving low-level exertions, either sustained or intermittent, such as standing work.

Postural Stability and Fatigue

Gribble and Hertel (2004) suggested that fatigue in the lower extremities, including the hips, impairs postural control. In addition, Freitas et al. (2005) found in adults that COP displacement speed increased after standing for 30 min. More recently, Gimmon, Riemer, Oddsson, and Melzer (2011) concluded that localized fatigue of plantar flexor muscles may alter postural stability, and Wojcik et al. (2011) showed that fatigue in lower-limb joint muscles resulting from high exertions affect postural control through an increase in joint torque variability. Therefore, it was hypothesized that fatigue in the lower leg muscles after 5 hr of standing may influence postural sway. In our study, when compared to baseline, the increase in COP displacement speed was not significant immediately after 5 hr of standing work but was significant 30 min postwork. This finding may not be a paradox as the long-term effects of fatigue may be more pronounced 30 min to an hour post–fatiguing task (e.g., Adamo et al., 2002, 2009; Sogaard et al., 2003). Furthermore, the increase in fatigue between E1 and E2 periods was not significant; however, a small increment in fatigue might have led to a further increase in postural control alterations that resulted in a significant effect at time E2. This assumption is partly supported by the fact that COP displacement speed also increased on the control day but was not significant at time E1.

Overall, since COP displacement speed tends to increase both during the working day and the control day, it may be presumed that localized muscle fatigue may not be the only component contributing to a decrease in postural stability. Central effects acting on motor control functions (Gandevia, 2001) associated with a general fatigue of physical and/or mental origin may require further consideration.

Subjective Evaluation and Fatigue

Correlation between back and lower-limb discomfort and prolonged standing work has been shown (Antle & Côté, 2013; Drury et al., 2008). We observed that perception of lower-back and lower-limb discomfort was significantly higher immediately after standing work than at baseline. However, the perception of discomfort had vanished 30 min postwork, except for minor residual discomfort in the lower legs area for the older group. This drop, taken alone, would indicate a recovery after 30 min of rest. However, the dichotomy between the majority of subjective evaluations and the MTF objective measure at time E2, along with the lack of correlation, indicates that an absence of perception does not mean an absence of significant fatigue. This phenomenon is in agreement with previous findings whereby perception of fatigue had vanished after a 60-min (Adamo et al., 2002) or even 15-min (Adamo et al., 2009) recovery period. The results support the perspective that subjective perception may not be a good indicator of the long-term effects of fatigue.

CONCLUSIONS

Fatigue did not develop after the first 2 hr of standing work. However, it was strongly present after 5 hr of standing work with regular rest breaks and persisted at least 30 min postwork. The MTF method is sensitive to fatigue of long duration. Changes in postural stability may indicate fatigue; however, similar changes on the control day suggest the interference of factors other than long-term fatigue. The lack of congruence between subjective and objective methods underlines the strong limitation of subjective evaluation of the long-term effects of fatigue. Finally, age and gender effects are not conspicuous. The findings are limited to the work cycle tested, and different work cycles and other performance measures may be envisaged to further understand the effects of long-term fatigue.

ACKNOWLEDGMENTS

This study was supported by grants from the Swiss State Secretariat for Economic Affairs (SECO), Federal Coordination Commission for Occupational Safety (FCOS), the Swiss Accident Insurance Agency (Suva), and the Ecuadorian Secretariat for Education, Science, Technology, and Innovation to M. G. Garcia. The authors thank C. Nicoletti for her assistance in the experiments, P. Johnson and J. H. Kim for their last update of the software designed to control and measure muscle twitch force, and Rolf van de Langenberg for software assistance to measure postural stability.

KEY POINTS

- Authors of previous studies investigated long-term fatigue during low-level exertions in the upper limbs; however, the extent to which long-term fatigue develops and persists in the lower limbs after prolonged standing work has received little attention.
- The results suggest that long-term fatigue develops after 5 hr of standing work with regular 5-min rest breaks and persists at least 30 min after a seated recovery period without being perceived.
- Subjective evaluation of discomfort may not be sensitive to the long-lasting effects of fatigue in contrast with objective measurements.
- Specific objective tests, such as muscle twitch force, are preferable for quantifying long-term muscle fatigue.

REFERENCES

Adamo, D. E., Khodaee, M., Barringer, S., Johnson, P. W., & Martin, B. J. (2009). Low mean level sustained and intermittent grip exertions: Influence of age on fatigue and recovery. *Ergonomics*, *52*, 1287–1297.

Adamo, D. E., Martin, B. J., & Johnson, P. W. (2002). Vibration-induced muscle fatigue, a possible contribution to musculoskeletal injury. *European Journal of Applied Physiology*, *88*, 134–140.

Antle, D. M., & Côté, J. N. (2013). Relationships between lower limb and trunk discomfort and vascular, muscular and kinetic outcomes during stationary standing work. *Gait & Posture*, *37*, 615–619.

Armstrong, T. J., Buckle, P., Fine, L. J., Hagberg, M., Jonsson, B., Kilbom, A., . . . Viikari-Juntura, E. R. (1993). A conceptual model for work-related neck and upper-limb musculoskeletal disorders. *Scandinavian Journal of Work, Environment & Health*, *19*, 73–84.

Blangsted, A. K., Sjogaard, G., Madeleine, P., Olsen, H. B., & Sogaard, K. (2004). Voluntary low-force contraction elicits prolonged low-frequency fatigue and changes in surface electromyography and mechanomyography. *Journal of Electromyography and Kinesiology*, *15*, 138–148.

Brownie, J., & Martin, B. J. (2015). *Muscle fatigue and discomfort associated with standing and walking: Comparison of work surfaces*. Unpublished manuscript.

Cham, R. F., & Redfern, M. S. (2001). Effect of flooring on standing comfort and fatigue. *Human Factors*, *43*, 381–391.

Côté, J. (2014). Fatigue as a precursor to MSD in the injury trajectory? In M. F. Levin (Ed.), *Progress in motor control: Skill,* *learning, performance, health, and injury* (pp. 206–210). New York, NY: Springer.

D'Souza, J. C., Franzblau, A., & Werner, R. A. (2005). Review of epidemiologic studies on occupational factors and lower extremity musculoskeletal and vascular disorders and symptoms. *Journal of Occupational Rehabilitation*, *15*, 129–165.

Desmedt, J. E., & Hainaut, K. (1968). Kinetics of myofilament activation in potentiated contraction: Staircase phenomenon in human skeletal muscle. *Nature*, *217*, 529–532.

Drury, C. G., Hsiao, Y. L., Jospeh, C., Joshi, S., Lapp, J., & Pennathur, P. R. (2008). Posture and performance: Sitting vs. standing for security screening. *Ergonomics*, *51*, 209–307.

Edwards, R. H., Hill, D. K., Jones, D. A., & Merton, P. A. (1977). Fatigue of long duration in human skeletal muscle after exercise. *Journal of Physiology*, *272*, 769–778.

Edwards, R. H. (1981). Human muscle function and fatigue. *Ciba Foundation Symposium*, *82*, 1–18.

Edwards, R. H. (1988). Hypotheses of peripheral and central mechanisms underlying occupational pain and injury. *European Journal of Applied Physiology*, *57*, 275–281.

Elsner, G., Nienhaus, A., & Beck, W. (1996). Arthrosis of the knee and work-related factors. *Sozial-Und Praventivmedizin*, *41*, 98–106.

Enoka, R. M., & Stuart, D. G. (1992). Neurobiology of muscle fatigue. *Journal of Applied Physiology*, *72*, 1631–1648.

Freitas, S. M., Wieczorek, S. A., Marchetti, P. H., & Duarte, M. (2005). Age-related changes in human postural control of prolonged standing. *Gait & Posture*, *22*, 322–330.

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews*, *81*, 1725–1789.

Geurts, A., Nienhuis, B., & Mulder, T. (1993). Intrasubject variability of selected force-platform parameters in the quantification of postural control. *Archives of Physical Medicine and Rehabilitation*, *74*, 1144–1150.

Gimmon, Y., Riemer, R., Oddsson, L., & Melzer, I. (2011). The effect of plantar flexor muscle fatigue on postural control. *Journal of Electromyography and Kiniesiology*, *21*, 922–928.

Graf, M., Krieger, R., Läubli, T., & Martin, B. J. (2015). *Should we recommend people to stand more than sit at work?* Unpublished manuscript.

Gregory, D. E., & Callaghan, J. P. (2008). Prolonged standing as a precursor for the development of low back discomfort: An investigation of possible mechanisms. *Gait & Posture*, *28*, 86–92. doi:10.1016/j.gaitpost.2007.10.005

Gribble, P. A., & Hertel, J. (2004). Effect of lower-extremity muscle fatigue on postural control. *Archives of Physical Medicine and Rehabilitation*, *85*, 589–592.

Hansen, L., Winkel, J., & Jorgensen, K. (1998). Significance of mat and shoe softness during prolonged work in upright position: Based on measurements on low back muscle EMG, foot volume changes, discomfort and ground force reactions. *Applied Ergonomics*, *29*, 217–224.

Hunter, S. K., Critchlow, A., & Enoka, R. M. (2004). Influence of aging on sex differences in muscle fatigability. *Journal of Applied Physiology*, *97*, 1723–1732.

Johnson, M. A., Polgar, J., Weightman, D., & Appleton, D. (1973). Data on the distribution of fibre types in thirty-six human muscles: An autopsy study. *Journal of the Neurological Sciences*, *18*, 111–129.

Johnson, P. W., Ciriello, V. M., Kerin, K. J., & Dennerlein, J. T. (2013). Using electrical stimulation to measure physiological changes in the human extensor carpi ulnaris muscle after prolonged low-level repetitive ulnar deviation. *Applied Ergonomics*, *44*, 35–41.

Johnston, R. B., Howard, M. E., Cawley, P. W., & Losse, G. M. (1998). Effect of lower extremity muscular fatigue on motor control performance. *Medicine and Science in Sports and Exercise*, *30*, 1703–1707.

Jones, D. A. (1996). High and low-frequency fatigue revisited. *Acta Physiologica Scandinavica*, *156*, 265–270.

Kim, J. Y., Stuart-Buttle, C., & Marras, W. S. (1994). The effects of mats on back and leg fatigue. *Applied Ergonomics*, *25*, 29–34. doi:10.1016/0003-6870(94)90028-0

King, P. M. (2002). A comparison of the effects of floor mats and shoe in-soles on standing fatigue. *Applied Ergonomics*, *33*, 477–484. doi:10.1016/s0003-6870(02)00027-3

Kuorinka, I., Jonsson, B., Kilborn, A., Vinterberg, H., Biering-Sorensen, F., Andersson, G., & Jorgensen, K. (1987). Standardised Nordic questionnaires for the analysis of musculoskeletal symptoms. *Applied Ergonomics*, *18*, 233–237.

Lin, Y. H., Chen, C. Y., & Cho, M. H. (2012). Effectiveness of leg movement in reducing leg swelling and discomfort in lower extremities. *Applied Ergonomics*, *43*, 1033–1037. doi:10.1016/j.apergo.2012.03.002

Madeleine, P., Voigt, M., & Arendt-Nielsen, L. (1998). Subjective, physiological and biomechanical responses to prolonged manual work performed standing on hard and soft surfaces. *European Journal of Applied Physiology*, *77*, 1–9.

Nakata, M., Hagner, I. M., & Jonsson, B. (1992). Perceived musculoskeletal discomfort and electromyography during repetitive light work. *Journal of Electromyography and Kinesiology*, *2*, 103–111. doi:10.1016/1050-6411(92)90021-a

Orlando, A. R., & King, P. M. (2004). Relationship of demographic variables on perception of fatigue and discomfort following prolonged standing under various flooring conditions. *Journal of Occupational Rehabilitation*, *14*, 63–76.

Paillard, T. (2011). Effects of general and local fatigue on postural control: A review. *Neuroscience and Biobehavioral Reviews*, *36*, 162–176.

Parent-Thirion, A., Vermeylen, G., van Houten, G., Lyly-Yrjänäinen, M., Biletta, I., & Cabrita, J. (2012). *Fifth European Working Conditions Survey overview report* (EF1182). Dublin, Ireland: European Foundation for the Improvement of Living and Working Conditions.

Rankin, L. L., Enoka, R. M., Volz, K. A., & Stuart, D. G. (1988). Coexistence of twitch potentiation and tetanic force decline in rat hindlimb muscle. *Journal of Applied Physiology*, *65*, 2687–2695.

Redfern, M., & Cham, R. (2000). The influence of flooring on standing comfort and fatigue. *American Industrial Hygiene Association Journal*, *61*, 700–708.

Riddle, D., Pulisic, M., Pidcoe, P., & Johnson, R. E. (2003). Risk factors for plantar fasciitis: A matched case-control study. *Journal of Bone and Joint Surgery–American Volume*, *85A*, 872–877.

Ryan, G. A. (1989). The prevalence of musculo-skeletal symptoms in supermarket workers. *Ergonomics*, *32*, 359–371.

Sogaard, K., Blangsted, A. K., Jorgensen, L. V., Madeleine, P., & Sjogaard, G. (2003). Evidence of long term muscle fatigue following prolonged intermittent contractions based on mechano- and electromyograms. *Journal of Electromyography and Kinesiology*, *13*, 441–450.

Standing problem. (2005, August). *Hazards Magazine*. Retrieved from http://www.hazards.org/standing/

Waters, T. R., & Dick, R. B. (2014). Evidence of health risks associated with prolonged standing at work and intervention effectiveness. *Rehabilitation Nursing*. Advance online publication.

Westerblad, H., Bruton, J. D., Allen, D. G., & Lännergren, J. (2000). Functional significance of Ca2+ in long-lasting fatigue of skeletal muscle. *European Journal of Applied Physiology*, *83*, 166–174.

Wojcik, L. A., Nussbaum, M. A., Lin, D. D., Shibata, P. A., & Madigan, M. L. (2011). Age and gender moderate the effects of localized muscle fatigue on lower extremity joint torques used during quiet stance. *Human Movement Science*, *30*, 574–583. doi:10.1016/j.humov.2010.03.008

Zander, J. E., King, P. M., & Ezenwa, B. N. (2004). Influence of flooring conditions on lower leg volume following prolonged standing. *International Journal of Industrial Ergonomics*, *34*, 279–288. doi:10.1016/j.ergon.2004.04.014

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Date received: February 14, 2015
Date accepted: May 12, 2015