Muscular and Vascular Issues Induced by Prolonged Standing With Different Work–Rest Cycles With Active or Passive Breaks

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Objective: The aim of this study was to evaluate the long-lasting motor, behavioral, physiological, and perceptual effects of prolonged standing work in three work–rest cycle conditions including passive or active rest breaks.

Background: Muscle fatigue has been evidenced after prolonged standing work through physiological and neuromotor measures. It has been postulated that muscle fatigue induced by prolonged work could be attenuated by appropriate scheduling of work and rest periods. However, investigations in this domain remain limited.

Method: Thirty participants simulated standing work for 5 hr with work–rest cycles of short, medium, or long standing periods including passive or active breaks. Lower-leg muscle twitch force (MTF), muscle oxygenation, lower-leg volume, postural stability, force control, and discomfort perception were quantified on 2 days.

Results: Prolonged standing induced significant changes in all measures immediately after 5 hr of work, indicating a detrimental effect in long-lasting muscle fatigue, performance, discomfort, and vascular aspects. Differences in the measures were not significant between work cycles and/or break type.

Conclusion: Similar physiological and motor alterations were induced by prolonged standing. The absence of difference in the effects induced by the tested work–rest cycles suggests that simply altering the work–rest cycle may not be sufficient to counteract the effects of mainly static standing work. Finally, standing for 3 hr or more shows clear detrimental effects.

Application: Prolonged standing is likely to contribute to musculoskeletal and vascular symptoms. A limitation to less than 3 hr of mostly static standing in occupational activities could avoid alterations leading to these symptoms.

Keywords: muscle twitch force, fatigue, standing, oxygenation, postural stability, performance, edema, discomfort

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INTRODUCTION

Approximately 50% of the workforce in the European Union reported working in a standing posture most of their workday (Graf, Krieger, Läubli, & Martin, 2015). Prolonged standing work has been related to several musculoskeletal disorders (MSDs), including low-back pain (Coenen et al., 2017; Gallagher, Campbell, & Callaghan, 2014; Waters & Dick, 2014), ankle and foot pain (Messing, Tissot, & Stock, 2008; Werner, Gell, Hartigan, Wiggermann, & Keyserling, 2010), knee pain (Cham, Redfern, 2001), and lower-leg discomfort (Brownie & Martin, 2015; Garcia, Graf, & Laubli, 2017; Garcia, Laubli, & Martin, 2015; Garcia, Wall, Steinhilber, Laubli, & Martin, 2016). It has also been associated with cardiovascular problems, as reviewed by Waters and Dick (2014), such as varicose veins (Tabatabaeifar et al., 2015; Tüchsen, Hannerz, Burr, & Krause, 2005), and leg swelling (Chester, Rys, & Konz, 2002; Lin, Chen, & Cho, 2012). Several studies have used physiological or subjective measures to evaluate the effects of prolonged standing (Redfern & Cham, 2000). However, these studies are limited and most of them evaluated standing work for periods less than 2 hr (Redfern & Cham, 2000). Localized muscle fatigue has attracted attention, as it is widely considered a precursor of MSDs (Armstrong et al., 1993; Côté, 2014; Edwards, 1988) and recently presented as "fatigue failure process" (Gallagher & Schall, 2017).

Prolonged standing work and its relation with lower-limb fatigue has been evaluated thorough postural stability tests (Antle & Côté, 2013; Hansen, Winkel, & Jørgensen, 1998; Madeleine, Voigt, & Arendt-Nielsen, 1998; Zhang, Drury, & Woolley, 1992), muscle twitch force (MTF; Brownie & Martin, 2015; Garcia et al., 2015,

2016), subjective evaluations (Redfern & Cham, 2000; Wiggermann & Keyserling, 2013), and surface electromyography (EMG; Halim, Omar, Saman, & Othman, 2012; Madeleine et al., 1998). These measurements focus on quantifying lower-limb fatigue related to the task. In particular, MTF is able to objectively quantify a component of muscle fatigue commonly called long-lasting muscle fatigue (Edwards, Hill, Jones, & Merton, 1977; Garcia et al., 2016; Westerblad, Bruton, Allen, & Lannergren, 2000), which could persist up to 24 hr postwork (Edwards et al., 1977) and also results from low-level intermittent exertions, such as prolonged standing (Garcia et al., 2015, 2016).

Performance-related measures, such as dynamic force control test, have been used to evaluate the effects of a fatiguing task (Huysmans, Hoozemans, van der Beek, de Looze, & van Dieën, 2008). These authors observed that tracking performance was significantly affected by fatigue. In addition, several studies (Antle & Côté, 2013; Cham & Redfern, 2001; Hansen et al., 1998) used postural stability tests to evaluate the motor effects of prolonged standing. The underlying assumption is that an increase in center-of-pressure (COP) displacement corresponds to an increase of body movement in response to muscle discomfort and fatigue (Redfern & Cham, 2000).

Measurements such as leg volume (Blättler, Thomae, & Amsler, 2016; Cham & Redfern, 2001; Hansen et al., 1998; Zander, King, & Ezenwa, 2004) and blood flow (Antle & Côté, 2013) have been used to evaluate the effects of prolonged standing on detrimental vascular outcomes. In addition, it has been proposed that standing work discomfort may have a vascular origin (Antle & Côté, 2013), and blood flow and oxygenation may modulate muscle fatigue (Hepple, 2002; Murthy, Kahan, Hargens, & Rempel, 1997; Sjogaard, Savard, & Juel, 1988).

No study has utilized these measurements to evaluate the effect of different standing work–rest cycles. Alteration of work–rest cycle may relieve the effect of the task on fatigue (Adamo, Khodaee, Barringer, Johnson, & Martin, 2009; Wood, Fisher, & Andres, 1997).

In jobs involving low-level and prolonged loads to the musculoskeletal system, several studies have suggested that more physical variation may be a positive intervention in the prevention of MSDs; however, current evidence is weak (Mathiassen, 2006). A recent study suggested that having a more active standing posture may relieve the effects on discomfort and leg volume changes (Karimi, Allahyari, Azghani, & Khalkhali, 2016). In addition, seated breaks between prolonged standing exposures have been shown to relieve effects of standing on low-back pain development (Gallagher et al., 2014). To our knowledge, no study has evaluated different work–rest cycles with active and passive break interventions during prolonged standing.

The aim of the present study was to investigate the effects of prolonged standing on MTF, postural stability, motor control, subjective perception of discomfort, and lower-leg swelling and vascular changes on three different work–rest cycles with active or passive rest breaks. A secondary aim was to understand the role of some fatigue mechanisms. The study was designed to test the following hypothesis: Change in fatigue magnitude with work–rest cycles and/or rest-break types should be reflected by changes in physiological and, to some extent, psychophysical variables associated with muscle fatigue.

METHOD

Participants

Thirty healthy individuals (15 males, 15 females) between 18 and 65 years old participated in the study. Approval was obtained from the ethics committee of ETH Zurich, and all participants gave written informed consent prior to the experiments. This research complied with the tenets of the Declaration of Helsinki. The participants' mean age and weight (± *SD*) were 30 (± 12) years and 68 (± 13.9) kg, respectively. They were not divided into groups as previous comparable studies did not show significant age and/or gender effects (Garcia et al., 2015). Exclusion criteria included any musculoskeletal, neurological, or vascular problems that hinder the ability to perform standing work for more than 5 hr. All participants received a financial compensation for their involvement in the study.

Dependent Variables

Gastrocnemius-soleus MTF amplitude and duration, COP displacement speed and 95% confidence ellipse area, soleus muscle oxygenation

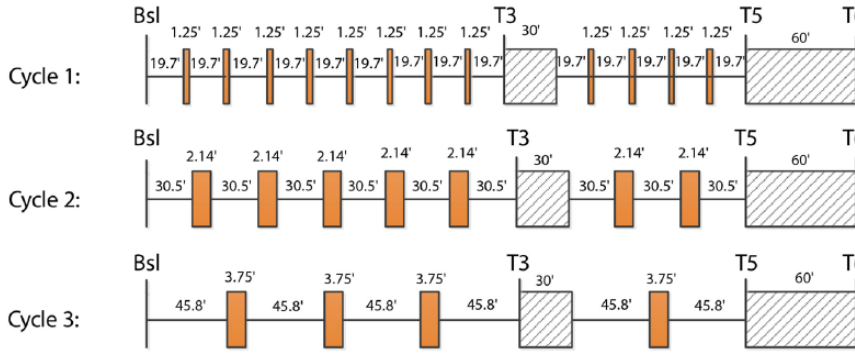

Figure 1. Work–rest cycles. The horizontal lines represent the standing work periods, the solid boxes represent the rest breaks (active or passive), and the patterned boxes represent the seated rest breaks (lunch and postwork). Measurements were performed at baseline (Bsl), after the first 3 hr of work (T3), immediately after the end of the workday (T5), and 1 hr postwork at the end of the seated recovery period (T6).

(HbT and StO_2), lower-leg volume, perception of discomfort, and force control magnitude (root mean square tracking error [RMSE]) were collected during two nonconsecutive simulated standing workdays for each participant.

Experimental Design

Three work–rest cycles including, respectively, short, medium, and long standing periods (Figure 1) with two break types (active or passive) were tested. Each participant was randomly assigned to two out of the six possible schedules following an incomplete balanced block design where each of the conditions occurred equally frequently and randomly on the first or second session. Thus, 10 participants performed each single condition. For example, one participant could have been assigned the same cycle repeated with a different break type or two different cycles with the same break type. Only one condition (cycle–break type) was tested in an experimental day.

During standing work periods, the participants performed light manual tasks, including computer work and reading books, that could be alternated to prevent boredom. All tasks were performed on a workbench adjusted to elbow height and close to the participant to avoid far reaches. The work area was constrained to a maximum of 1.5 m^2, as is common in manufacturing industries. Participants were not allowed to walk (performing more than two consecutive steps) or rest their arms on the worktable; however, body weight shifting and movement of the legs were not constrained. All participants were provided with the same type of new sport shoes. A similar experimental protocol was described in two previous related studies (Garcia et al., 2015, 2016).

The total amount of standing time for all work–rest cycles was 275 min, and the total amount of rest breaks was 15 min. In addition, a 30-min seated lunch break followed the 3rd hr of work, and 1 hr seated recovery period was provided at the end of the standing workday. A lunch meal and beverages were offered during the lunch break, and water was provided throughout the day. Two break types separated working periods; a passive or an active break was performed depending on the assigned schedule. However, each workday included only one break type. Passive breaks consisted in remaining seated on an armchair for the required time. Active breaks consisted of three activities: (a) low-force pedaling while seated, (b) elevating the legs and resting them stretched and supported while seated, and (c) one leg balancing and stepping on the toes 15 times with each leg while standing. Break activities were assigned randomly to participants but balanced throughout the day and across participants.

Measurements of the dependent variables (listed earlier), with the exception of muscle oxygenation, were performed before the start of the

Figure 2. Muscle twitch force test setup for the gastrocnemius-soleus muscles.

workday at baseline, after the first 3 hr of work (T3), immediately after the end of the workday (T5), and 1 hr postwork at the end of the seated recovery period (T6), as illustrated in Figure 1. Muscle oxygenation was measured every 45 min. The complete duration of the experimental sessions was about 7 hr. Participants were required to avoid high-exertion physical activities, such as weight lifting and running, at least 24 hr prior to each session. Each experimental session was performed at least 2 days apart within a week for each participant. In addition, no more than 2 days prior to the first experimental day, participants performed a 3-hr training session for the dynamic force control test.

Apparatus and Procedure

MTF. The present study followed the procedure detailed in our previous studies to measure the MTF of the gastrocnemius-soleus muscles (Garcia et al., 2015, 2016). While sitting in a comfortable armchair, the participant rested the right foot on a fixed plate with a knee flexion angle of 60° and an ankle dorsiflexion angle of 0° from the neutral anatomical posture. The fixed plate was equipped with a force sensor connected to an amplifier (Figure 2). The knee was strapped to the armchair to avoid upward movements of the leg during the stimulation. The participant maintained a relaxed posture during the measurement period, confirmed verbally and through force signal monitoring. Pregelled electrodes (5 × 5 cm) were placed on the skin over the motor point area of the gastrocnemius and soleus muscles (Botter et al., 2011) and over the upper part of the distal gastrocnemius tendon, respectively. The electrodes' locations were marked to ensure identical placement on the second experimental day.

Electrical stimulation was applied through a Digitimer (Ft. Lauderdale, FL) stimulator (DS7A) driven by a pulse generator (DG2A) at a frequency of 2 Hz, with an intensity between 10 and 30 mA and a pulse duration of 1 ms. For each participant, the stimulation intensity corresponded to the maximum tolerable discomfort associated with the largest twitch force. The same intensity was used on both experimental days. The twitch force signal was sampled at 1000 Hz by a custom LabVIEW program (National Instruments, Austin, TX). The program also computed and displayed the muscle twitch amplitude and duration (= contraction time + 0.5 relaxation time) in real time for visualization. This procedure was done to determine the stimulation-induced potentiation state of the muscle. The gastrocnemius-soleus MTF steady state occurs usually after about 3 min of potentiation, as described by Adamo, Martin, and Johnson (2002); Garcia et al., 2015, 2016; and Kim and Johnson (2014). After reaching the steady state, three consecutive series of 30 twitches with a coefficient of variation under 3% were recorded (Adamo et al., 2002). Hence, each period of muscle stimulation lasted about 4 min. MTF amplitude and duration were measured at baseline, T3, T5, and T6 (Figure 1).

Postural stability. The method and procedure were identical to our previous study Garcia et al. (2015). COP *x, y* coordinates were recorded at a frequency of 1000 Hz while the participant stood upright on a force plate with the eyes closed for 30 s. Footprints were marked on the force plate to obtain the same feet placements for each test. The COP displacement speed and corresponding 95% confidence ellipse area were calculated using Matlab and following Geurts, Nienhuis, and Mulder (1993) and Oliveira, Simpson, and Nadal (1996). Previous studies have suggested that the changes in COP 95% confidence ellipse area and mean speed provide variability and postural control information associated with fatigue (Chiari, Rocchi, & Cappello, 2002; Geurts et al., 1993). Hence, postural stability was assessed at baseline, T3, T5, and T6.

Lower-leg volume. The lower-leg volume was measured using a volumetric edema gauge. The device consisted of a water tank filled up to the overflow level. Most of the lower leg could be submerged in water while the participant was in a seated posture with the lower leg perpendicular to the ground. The water displaced out of the tank by lower-leg immersion was weighted and the value recorded. The lower-leg volume was measured at baseline, T5, and T6.

Dynamic force control. A 1-min-duration isometric tracking task was used to test force control. A large white cursor was displayed on a computer monitor. This target cursor was controlled by a random signal (0–0.5 Hz frequency bandwidth) and moved along a vertical axis. The extreme values of the magnitude scale on this axis corresponded to 0% (top) and 20% (bottom) of the participant's maximal voluntary contraction, respectively. A second cursor (smaller and blue) was also presented on the screen. This latter was controlled by the force signal generated by pressure of the foot (plantar flexion) on the force transducer. The posture was identical for the MTF and force control measurements. The participant was instructed to track the white target cursor movement by keeping the foot-controlled blue cursor inside the white target. Force exertion and cursor displacement (pressure, down; relaxation, up) were fully compatible. The force signal was sampled at 50 Hz and low pass filtered (second-order Butterworth filter, 10 Hz cutoff frequency). The RMSE was evaluated at baseline, T3, T5, and T6 to quantify the performance.

Lower-leg muscle oxygenation. OxyPerm near-infrared spectroscopy surface sensors (Biomedical Optics Research Laboratory, Zurich, Switzerland), with a light spectrum range of 700 to 900 nm, were placed over the soleus muscle to measure total hemoglobin (HbT), given by the sum of oxygenated hemoglobin (O_2Hb) and deoxygenated hemoglobin (HHb), and oxygen saturation (StO_2) on the soleus muscle. StO_2 reflects the balance between the supply of oxygen and its consumption in the muscle region under the sensors (Ferrari, Muthalib, & Quaresima, 2011). Moreover, HbT represents the changes in the total volume of hemoglobin in the tested muscle area (Quaresima et al., 2001). HbT and StO_2 were measured every 45 min from the beginning to the end of the workday, which corresponded to seven measurements. During each measurement, the participant stood still for 60 s. Data were recorded at 100 Hz and a third-order lowpass Butterworth filter with a cutoff frequency of 0.05 Hz was applied. Post-work measurements were not possible due to incompatibility with lower-leg immersion.

Subjective evaluation. Discomfort level of the lower body (feet, ankles, lower leg, knees, upper leg/hip, and lower back) was evaluated using an adapted Nordic questionnaire (Kuorinka et al., 1987) as presented by Garcia et al. (2015). The questionnaire included 10-cm visual analog scales associated with body areas, on which vertical marks were placed to rate discomfort (0–10). Scales for left and right body areas were grouped due to their high correlation (Pearson's correlation coefficient > .7).

Data Analysis

All data were analyzed using mixed models to consider fixed (time, work cycle, break type) and random effects (subject, day). Day (within participant) was also included as a random effect as measures taken within a day are usually correlated. Because percentage changes were of interest in the present study, all data were log transformed for the statistical analysis. In order to address our hypotheses, first, we analyzed data with a model using time (baseline, T3, T5, T6) as the independent variable, participant as a random effect, and day within-participant random effect (Model A). (Note that time has seven levels for StO_2 and HbT measures.) Then, to investigate the effect of work–rest cycle (see Figure 1), a second model used time as independent variable, participant as a random effect, day (Day 1, Day 2) within-participant random effect, and the interaction of time and cycle (Cycle 1, Cycle 2, Cycle 3) (Model B). To investigate the effect of break type (active, passive), a third model was used with time as independent variable, participant as a random effect, day (Day 1, Day 2) within-participant random effect, and the interaction of time and break type (active, passive) (Model C). All analyses were performed with a variance-components covariance structure and a residual maximum

TABLE 1: Mixed Model A Results for Time

	Time			
Measurement	Num *df*	Den *df*	*F* Ratio	*p*
MTF amplitude	3	161	26.30	**<.0001**
MTF duration	3	161	29.90	**<.0001**
COP speed	3	165	21.75	**<.0001**
COP ellipse area	3	165	3.57	**.015**
Volume	2	118	48.52	**<.0001**
Tracking RMSE	3	173	5.66	**.001**
NIRS StO_2	6	250	21.63	**<.0001**
NIRS HbT	6	250	5.99	**<.0001**
Discomfort lower back	3	417	33.28	**<.0001**
Discomfort hip/upper leg	3	417	48.01	**<.0001**
Discomfort knees	3	417	55.28	**<.0001**
Discomfort lower leg	3	417	129.5	**<.0001**
Discomfort ankles	3	417	51.85	**<.0001**
Discomfort feet	3	417	217.2	**<.0001**

Note. COP = center of pressure; Den = denominator degrees of freedom; HbT = total hemoglobin; MTF = muscle twitch force; NIRS = near-infrared spectroscopy; Num = numerator degrees of freedom; RMSE = root mean square error; StO_2 = oxygen saturation. Bold font indicates significant values, $\alpha = .05$.

likelihood estimation. In addition, differences of least square means were computed to compare each measure as a function of time. The level of significance was set to $\alpha = .05$. For comparison simplification, means and standard error values refer to changes relative to baseline after normalization, whereas *p* values correspond to the analysis applied to the log-transformed raw data. Data analyses were conducted using SAS 9.4. Results illustrations are relative to baseline to facilitate the visualization of effects.

RESULTS

MTF

Time was a highly significant main effect for twitch amplitude and twitch duration (Table 1). However, time interactions with work–rest cycle and break type were not significant, as indicated in Tables 2 and 3, respectively. Hence, the following results correspond to Model A. Twitch amplitude was significantly lower at T3 ($M = 91.45\%$, $SE = 3.98\%$; $p = .04$), T5 ($M = 77.11\%$, $SE = 3.92\%$; $p < .0001$), and T6 ($M = 73.17\%$, $SE = 4.30\%$; $p < .0001$) than at baseline. Moreover, the measurements at T5 and T6 were significantly ($p < .0001$) lower than at T3 (Figure 3a). Twitch duration was significantly higher at T3 ($M = 104.39\%$, $SE = 1.02\%$; $p = .009$), T5 ($M = 105.05\%$, $SE = 1.27\%$; $p = .0004$), and T6 ($M = 112.45\%$, $SE = 1.78\%$; $p < .0001$) than at baseline (Figure 3b). Furthermore, twitch duration increased significantly ($p < .0001$) after the postwork recovery period, T6, compared with T5.

Postural Stability

Time was a highly significant main effect for COP displacement speed and 95% confidence ellipse area (Table 1). However, time interaction with work–rest cycle and break type were not significant, as indicated in Tables 2 and 3, respectively. Hence, the following results correspond to Model A. COP displacement speed was significantly slower at T3 ($M = 99.17\%$, $SE = .17\%$; $p < .0001$), T5 ($M = 98.72\%$, $SE = .15\%$; $p < .0001$), and T6 ($M = 98.99\%$, $SE = .16\%$; $p < .0001$) when compared with baseline. In addition, COP displacement speed was significantly ($p = .004$) slower at T5 but not at T6, compared with T3. COP 95% confidence

TABLE 2: Mixed Model B Results for Cycle × Time

	Cycle × Time			
Measurement	Num *df*	Den *df*	F Ratio	*p*
MTF amplitude	8	155	.85	.56
MTF duration	8	155	.77	.63
COP speed	8	159	.74	.65
COP area	8	159	.87	.54
Volume	6	114	1.13	.35
Tracking RMSE	8	166	.64	.74
NIRS StO_2	14	238	.90	.55
NIRS HbT	14	238	.94	.52
Discomfort lower back	8	171	.26	.98
Discomfort hip/upper leg	8	411	3.30	**.001**
Discomfort knees	8	411	1.76	.08
Discomfort lower leg	8	411	.63	.75
Discomfort ankles	8	411	.78	.62
Discomfort feet	8	411	1.14	.33

Note. COP = center of pressure; Den = denominator degrees of freedom; HbT = total hemoglobin; MTF = muscle twitch force; NIRS = near-infrared spectroscopy; Num = numerator degrees of freedom; RMSE = root mean square error; StO_2 = oxygen saturation. Bold font indicates significant values, $\alpha = .05$.

ellipse area was significantly larger at T5 (M = 142.79%, SE = 11.03%; $p = .002$) and T6 (M = 135.35%, SE = 9.73%; $p = .02$) but not at T3 (M = 132.65%, SE = 8.44%; $p = .06$), compared with baseline.

Lower-Leg Volume

Time was a highly significant main effect for lower-leg volume (Table 1). However, time interaction with work–rest cycle and break type were not significant, as indicated in Tables 2 and 3, respectively. Hence, the following results correspond to Model A. Lower-leg volume was significantly larger at T5 (M = 102.26%, SE = .27%; $p < .0001$) and T6 (M = 101.39%, SE = .23%; $p < .0001$), compared with baseline (Figure 4). However, lower-leg volume was significantly smaller ($p = .0003$) after the postwork recovery period, T6, compared with T5.

Dynamic Force Control

Time was a highly significant main effect for the RMSE (Table 1). However, time interaction with work–rest cycle and break type were not significant, as indicated in Tables 2 and 3, respectively. Hence, the following results correspond to Model A. RMSE was significantly higher at T5 (M = 107.75%, SE = 2.42%; $p = .003$) but not at T3 (M = 104.29%, SE = 1.95%; $p = .13$) and T6 (M = 99.16%, SE = 1.9%; $p = .44$), compared with baseline. Moreover, RMSE was significantly lower ($p < .03$) after the postwork recovery period, T6, compared with T3 and T5.

Lower-Leg Muscle Oxygenation

Time (seven measures) was highly significant for StO_2 and HbT (Table 1). The interaction of time with work–rest cycle was not significant for either measure, as indicated in Table 2. However, the interaction of time with break type was significant only for HbT (Table 3). Hence, the following results correspond to Model C for HbT and Model A for StO_2.

For the active break type, HbT Measures 2 to 5 were not significantly different from the measure at baseline; however, Measures 6 and 7, performed after the 4th hr (M = 105.50%, SE = 2.59%; p = .005) and the 5th hr (M = 108.48%, SE = 1.67%; $p < .0001$) of standing work, respectively, were significantly higher than at baseline. For the passive break type, only HbT Measures 3 and 5,

TABLE 3: Mixed Model C Results for Break × Time

	Break × Time			
Measurement	Num *df*	Den *df*	*F* Ratio	*p*
MTF amplitude	4	158	.82	.52
MTF duration	4	158	.67	.62
COP speed	4	162	2.20	.07
COP area	4	162	1.43	.23
Volume	3	116	.21	.89
Tracking RMSE	4	170	1.32	.27
NIRS StO_2	7	244	.81	.58
NIRS HbT	7	244	2.66	**.01**
Discomfort lower back	4	174	.69	.60
Discomfort hip/upper leg	4	414	1.81	.13
Discomfort knees	4	414	2.07	.08
Discomfort lower leg	4	414	1.17	.33
Discomfort ankles	4	414	3.56	**.007**
Discomfort feet	4	414	1.09	.36

Note. COP = center of pressure; Den = denominator degrees of freedom; HbT = total hemoglobin; MTF = muscle twitch force; NIRS = near-infrared spectroscopy; Num = numerator degrees of freedom; RMSE = root mean square error; StO_2 = oxygen saturation. Bold font indicates significant values, $\alpha = .05$.

performed at the 2nd hr ($M = 96.20\%$, $SE = 1.42\%$; $p = .01$) and the 3rd hr ($M = 95.54\%$, $SE = 1.89\%$; $p = .002$) of standing work, respectively, were significantly lower than at baseline.

StO_2 was significantly higher ($p < .0001$) after 45 min of standing, $M = 107.38\%$, $SE = 1.69\%$, and at each measurement time up to the end of the standing work, $M = 113.66\%$, $SE = 2.38\%$, compared with baseline. StO_2 did not increase significantly between Measures 2 and 4; however, the increase between Measures 4 ($M = 109.43\%$, $SE = 2.36\%$) and 5 ($M = 114.36\%$, $SE = 2.46\%$) was significant ($p = .006$). This increase persisted up to the last measurement.

Subjective Evaluation of Discomfort

The main effect of time was significant for discomfort ratings of the six body areas (Table 1). The interaction of time with work–rest cycle was significant only for the discomfort ratings of hip/upper leg (Table 2). The interaction of time with break type was significant only for the discomfort ratings of ankles (Table 3). In all body areas, discomfort was significantly (< .0001) higher at T3 and T5, compared with baseline, regardless of the cycle or break type. One-hour postwork discomfort ratings at T6 for the lower back, knees, hip/upper leg (all work–rest cycles), and ankles (only passive break type) were not significantly different from baseline. However, discomfort ratings for the lower legs, feet, and ankles (only active break type) were significantly higher (< .01) at T6 than at baseline. Perception of discomfort decreased significantly (< .0001) for all body areas after the postwork seated period (T6), compared with T5, regardless the cycle or break type. To explore the relevance of the interaction effect on hip/upper leg and ankles, least square mean differences to baseline of paired observations were computed. Discomfort ratings of the hip/upper leg were significantly higher (< .01) for work–rest Cycle 1, compared with Cycles 2 and 3, but only at T5. Discomfort ratings of the ankles were significantly higher (< .04) for active than for passive break type at T3, T5, and T6.

DISCUSSION

Three different work–rest cycles with two break types (active and passive) were investigated to assess possible physiological benefits of interventions aimed at reducing prolonged

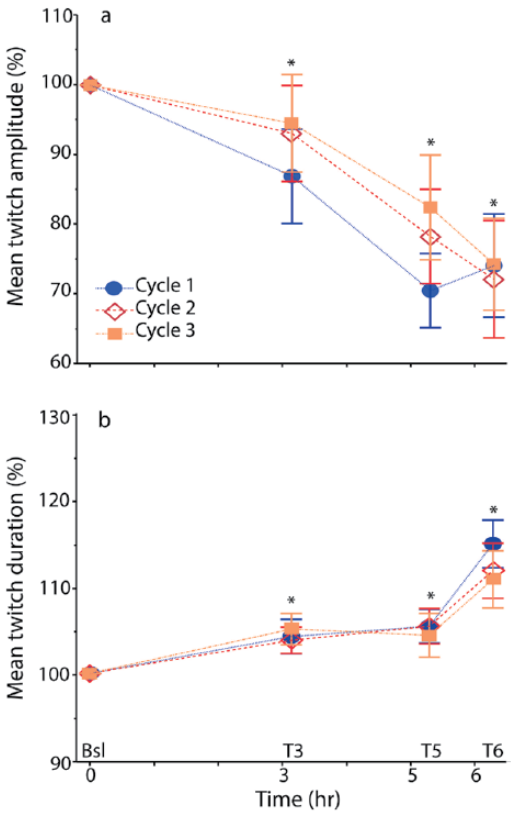

Figure 3. Changes in muscle twitch force (a) amplitude and (b) duration, relative (%) to baseline (Bsl). Vertical bars indicate standard errors. Asterisk (*) indicates a significant difference regardless of break type or work–rest cycle when compared with Bsl.

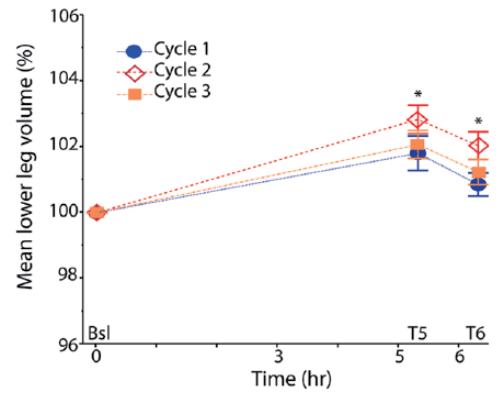

Figure 4. Changes in lower-leg volume relative (%) to baseline (Bsl). Vertical bars indicate standard errors. Asterisk (*) indicates a significant difference regardless of break type or work–rest cycle when compared to Bsl.

standing effects on muscle fatigue, performance, discomfort, and vascular issues. A significant effect of prolonged standing work was observed in all measures immediately after 5 hr of standing work. However, the influence of work cycles and/or break type was not significant. Hence, muscle fatigue and physiological and motor behaviors in response to prolonged standing, as opposed to shorter exposures, are discussed first to frame the context of effects and mechanisms. Then, last but not least, the influence of work cycles is presented in this context to more closely support conclusions.

Prolonged Standing and Muscle Fatigue

When compared with baseline, the significantly lower twitch amplitude and higher twitch duration observed immediately after 5 hr of standing work and their corresponding persistence or exacerbation for at least 1 hr postwork corroborate our previous studies with different work–rest cycles (Garcia et al., 2015, 2016). This finding shows that within a large range of work–rest cycles (from 19.7 min work and 1.25 min rest here to 110 min work and 5 min rest in Garcia et al., 2016) with the same total standing duration, prolonged standing leads to long-lasting muscle fatigue. Furthermore, we previously concluded that 2 hr of standing work does not correspond to clear signs of long-lasting fatigue (Garcia et al., 2015, 2016). However, the significant increase in twitch duration and decrease in twitch amplitude observed here after 3 hr of standing present a clear indication of muscle fatigue. In terms of muscle fatigue, which is considered a factor in MSDs (Côté, 2014; Edwards et al., 1977; Gallagher & Schall, 2017), 2 hr of standing work is likely acceptable, but 3 hr may correspond to a critical duration because fatigue develops significantly. Moreover, subjective evaluation of discomfort increased significantly after 3 hr and 5 hr of standing work. However, ratings return to baseline level after 1 hr postwork. This finding corroborates previous studies suggesting that long-lasting fatigue phenomena are not subjectively perceived (Adamo et al., 2002, 2009; Garcia et al., 2015).

Muscle Fatigue and Motor Performance

The dynamic control of force was not significantly altered after 3 hr of standing work, although signs of peripheral muscle fatigue had appeared. However, a significant degradation was observed immediately after 5 hr, but this performance decrement was no longer present after the recovery period. Several studies have illustrated motor control impairments induced by muscle fatigue (Cowley, Dingwell, & Gates, 2014; Johnston, Howard, Cawley, & Losse, 1998; Selen, Beek, & van Dieen, 2007). However, these effects were measured only immediately after a rather severe fatiguing task regimen (at least 7 on a 10-point subjective rating scale). Here, alteration of precise force control was induced by prolonged low-level exertion. The significant decrease in muscle force–producing capability combined with the increase in contraction and relaxation time may be invoked to explain performance alteration.

The mechanisms underlying these phenomena, which present a long time lag, cannot clarify alone the performance recovery 1 hr postwork, because twitch amplitude and duration show the persistence of fatigue. Furthermore, here the task is apparently depending on a single degree of freedom (plantar flexion-relaxation in a single plane). Hence, reorganization based on the exploitation of multijoint redundancy (Srinivasan & Mathiassen, 2012), redundant motor solutions (Cowley et al., 2014; Dingwell, Smallwood, & Cusumano, 2013), redundant intermuscular coordination (Cote, Feldman, Mathieu, & Levin, 2008; Madeleine & Farina, 2008), or variability in a multijoint neuromotor system (Mudie, Gupta, Green, & Clothier, 2016) should be considered. In other words, a compensation strategy may be adopted to produce the required foot pressure variations. Fatigue 1 hr postwork is primarily resulting from excitation-contraction coupling failure, as discussed later.

We postulate that reorganization of the motor command to drive the "least fatigued/most performant" motor unit pool may occur because the number of nonrecruited motor units by the task remains sufficiently large for the level of contraction required. This hypothesis is supported by the spatial redistribution of gastrocnemius and soleus activation with fatigue (Mesin & Farina, 2004; Vieira, Loram, Muceli, Merletti, & Farina, 2011), the variability in motoneuron activity (recruitment/derecruitment) with and after fatigue (Hunter & Enoka, 2003), and the variability of motoneuron input as a function of task during submaximal fatiguing contractions (Hunter & Enoka, 2003; Maluf, Shinohara, Stephenson, & Enoka, 2005; Rudroff, Poston, Shin, Bojsen-Moller, & Enoka, 2005). It could not be excluded that this change in motor command may also involve a contribution by upper-leg muscles in the production of foot pressure. An alternative/complementary explanation may be that improved learning of the task during the experimental day may emerge after 1 hr of recovery, especially because the task is repeated after 1 hr only. Indeed, the role of a learning effect is possible, as it was observed that performance was better on experimental Day 2, compared with Day 1.

The present results suggest that prolonged standing work has a negative effect on postural control, because it is assumed that a smaller COP area indicates a more stable posture (Schärli, van de Langenberg, Murer, & Müller, 2012). Johnston et al. (1998) noted that lower-extremity fatigue is reflected by a significant decrease in motor control performance and balance. This result agrees with the present findings, where significant lower-leg muscle fatigue was evidenced. However, postural stability altered by leg muscle fatigue, as observed here and other studies as well (Madeleine et al., 1998), is not strictly preserved by the possible change in motoneuron recruitment strategy evoked earlier despite a slowdown in COP displacement speed.

This apparent paradox, when considering previous results indicating an increase of COP displacement speed (Freitas, Wieczorek, Marchetti, & Duarte, 2005; Garcia et al., 2015) and the compensation mechanism suggested for force control, may be explained by versatility of the control mechanism. Due to the nature of the task, posture stability is less constrained than precision tracking and corresponds not to a force control task but rather to a coordination task. Hence, slowdown in COP speed due to reduced muscle force capability and the associated increase in COP displacement area may be considered

acceptable by the central nervous system because postural stability is far from being compromised. Indeed, it has been shown that the central nervous system may be satisfied with a "functionally good enough" muscle coordination as an alternative to an optimization process to reduce the cost of a complex reorganization of muscle coordination (de Rugy, Loeb, & Carroll, 2012; Lee, Thrasher, Layne, & Martin, 2016).

The present results underline the importance of the context in terms of fatiguing task and performance task. It may be assumed that compensation of muscle fatigue is most likely dependent on both the level of fatigue and task constraints, which is in line with changes in motoneuron activity as a function of task, as evoked earlier. In the present context, the role of central fatigue (Bigland-Ritchie, Furbush, & Woods, 1986; Gandevia, Enoka, McComas, Stuart, & Thomas, 1995) in the alteration of posture stability and/or the limitation of a significant reorganization of body segment/muscle coordination may not appear to be critical because the precision task, which is also dependent on central mechanisms, showed improvement at the end of the postwork recovery period.

Overall, integration of these data (muscle fatigue and degradation of motor performance) leads us to suggest that standing work in mostly static conditions (workspace limited to 1.5 m^2, as common in industrial settings) should be limited to less than 3 hr to avoid alterations of motor outcomes and associated long-term issues evidenced by MSDs.

Prolonged Standing and Vascular Outcomes

The present study showed that lower-leg volume significantly increased after 5 hr of prolonged standing work. Previous studies also reported a similar effect after half an hour (Antle & Côté, 2013), 2 hr (Hansen et al., 1998), and 4 hr (Zander et al., 2004) of standing work. Concomitantly, HbT tended to also increase, but this increase was significant only toward the end of the standing task in active break conditions (Figure 5). This finding may not be surprising, because an increment in muscle activity is likely to contribute to an increment in metabolism. Additionally, here we observed that

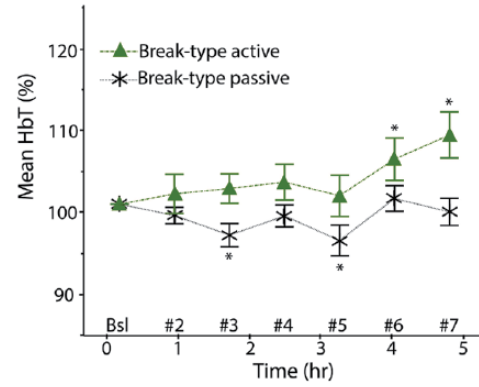

Figure 5. Changes in lower-leg muscle oxygenation HbT regardless of work-rest cycle and to baseline (Bsl). Vertical bars indicate standard errors. Asterisk (*) indicates a significant difference when compared to Bsl.

lower-leg volume had significantly decreased after the 1-hr postwork recovery seated break. Thus, disruption of the flux of potassium ions (K+), which are involved in muscle contraction mechanisms and whose loss is "the largest at low prolonged contractions" (Sejersted & Sjogaard, 2000), may be suspected to contribute to long-lasting muscle fatigue. Indeed, it may be suspected that an increase in water volume (Sjogaard, 1988) is associated with a dissipation of K+ in the extracellular space that reduces K+ uptake by the muscles (Sejersted & Sjogaard, 2000) and thus exacerbates muscle fatigue.

However, in the cases presented here, such phenomenon is not likely of significant importance because despite a reduction in volume, and thus recession of dissipation during the recovery period, muscle fatigue remains the same or slightly increases. Although prolonged low-level muscle activity K+ loss (Sejersted & Sjogaard, 2000) could be compensated by concomitant increase in HbT as observed in the active break condition, it must be observed that HbT does not change significantly in the passive break-type condition, and muscle fatigue magnitude is not different between conditions. Hence, these results support the assumption proposed earlier by Sejersted and Sjogaard (2000) and Sjogaard (1988) that a loss of K+ is not a major component of long-lasting fatigue, as

evidenced here. Long-lasting fatigue may remain primarily associated with the failure of excitation-contraction coupling involving calcium ions (Ca++) release mechanisms (Lamb, 2002; Ortenblad, Sjogaard, & Madsen, 2000; Westerblad, Duty, & Allen, 1993). Finally, muscle oxygenation is not likely to be an issue here, because StO_2 increases during the standing hours.

Work Cycles and Break Type

The evaluation of work–rest cycles has been considered as a potential solution to reduce the effects of workload in different fatiguing tasks (Eksioglu, 2006; Maresh et al., 2014). In the evaluation of four work schedules during prolonged standing, Van Dieen and Oude Vrielink (1998) concluded that longer breaks may help to relieve leg swelling, compared with shorter breaks. However, the amount of break presented in their study, 30 min after every 30 min of work, may not be applicable to all work environments. In the present study, work–rest schedules were based on the amount of break commonly given in industry, 15 min over a 5-hr work period plus 30 min of lunch break. However, this break duration (15 min total) may not be long enough to present a benefit or a difference when dividing it in various work–rest schedules, as presented in Figure 1. The differences among the present work–rest schedules are not significant in terms of any of the physiological or performance measurements presented in this study.

Regarding break type, the integration of physical variation during low-level prolonged or intermittent work has been suggested as an effective intervention; however; there is no strong evidence in this matter (Mathiassen, 2006). A recent study, concluded that changes in lower-leg muscle activity may reduce the effect on leg swelling (Karimi et al., 2016). Here, we incorporated changes of muscle activity during the breaks; however, no difference was observed compared with a passive break, except for muscle oxygenation. Uda, Seo, and Yoshinaga (1997) evaluated the use of intermittent exercise to reduce lower-leg swelling during standing work and suggested that activities such as knee bending reduce the swelling. The active exercises required during the break did not have an advantage over passive breaks; however, this result may be due to the duration of the activity. Dynamic/walking interventions have attenuated effects compared with a more static standing posture (Balasubramanian, Adalarasu, & Regulapati, 2008, 2009; Garcia et al., 2016). Hence, the integration of dynamic interventions may have a benefit if done during the standing period instead of the break.

Furthermore, periods of complete rest during a fatiguing schedule have been suggested to be necessary to alleviate muscle fatigue (Adamo et al., 2009; Bystrom, Mathiassen, & Fransson-Hall, 1991). Prolonged standing has also been associated with the development and aggravation of low-back pain (Ringheim, Austein, Indahl, & Roeleveld, 2015). The present results concur with these observations; however, we did not record low-back muscle EMG. Hence our interpretations remain focused on lower-limb issues. The amount of rest needed to alleviate the effects of prolonged standing still needs to be determined. In the present study, 15 min of break (plus a 30-min lunch break) during a 5-hr period of standing work is not enough to alleviate the effects of standing, no matter how it is distributed in the schedule. Thus, prolonged standing work should be limited to no more than 2 hr (Garcia et al., 2015, 2016). A work shift should perhaps combine periods of standing, sitting, and walking, which could be addressed in future studies.

Some limitations may apply to the present study. The study is limited to light manual work and would not apply to heavier-load manipulations. The interaction between vascular and/or edema issues and muscle fatigue may not be significant in the present context, but it would be risky to generalize to other activities involving a more significant loading of leg muscles. Finally, a detailed EMG analysis of leg muscle activity patterns via 2-D electrode arrays was precluded due to obvious limitations (complexity, conflict with leg volume and muscle oxygenation measures). Hence, the control of motor units' activation patterns could not be investigated to further the understanding of neuromotor mechanisms and application to the design of effective interventions aimed at counteracting muscle fatigue.

CONCLUSIONS

Muscle fatigue, vascular outcomes, and performance were affected by 5 hr of prolonged standing work regardless of the work–rest cycle or break type. Three hours of standing work showed a detrimental effect in terms of muscle fatigue but not performance. Subjective perception of discomfort does not reflect long-lasting fatigue. Alterations of the work–rest cycle may not be a sufficiently efficient solution for mainly static standing work, and an active break type does not have an advantage over a passive break type during work.

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KEY POINTS

- Physiological and performance measures were significantly altered after 5 hr of work, and some effects persisted for more than an hour after the end of work.
- The tested work–rest cycles do not seem to attenuate the effects of prolonged standing on motor outcomes and muscle fatigue.
- There is no evidence of potential advantage (or disadvantage) of active or passive break types for the tested work–rest cycles.
- Standing work for 3 hr or more leads to significant leg muscle fatigue.

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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.

Balasubramanian, V., Adalarasu, K., & Regulapati, R. (2008). Comparing stationary standing with an intermittent walking posture during assembly operations. *Human Factors and Ergonomics in Manufacturing*, *18*, 666–677.

Balasubramanian, V., Adalarasu, K., & Regulapati, R. (2009). Comparing dynamic and stationary standing postures in an assembly task. *International Journal of Industrial Ergonomics*, *39*, 649–654.

Bigland-Ritchie, B., Furbush, F., & Woods, J. J. (1986). Fatigue of intermittent submaximal voluntary contractions: Central and peripheral factors. *Journal of Applied Physiology*, *61*, 421–429.

Blättler, W., Thomae, H. J., & Amsler, F. (2016). Venous leg symptoms in healthy subjects assessed during prolonged standing. *Journal of Vascular Surgery: Venous and Lymphatic Disorders*, *4*, 455–462.

Botter, A., Oprandi, G., Lanfranco, F., Allasia, S., Maffiuletti, N., & Minetto, M. (2011). Atlas of the muscle motor points for the lower limb: Implications for electrical stimulation procedures and electrode positioning. *European Journal of Applied Physiology*, *111*, 2461–2471.

Brownie, J., & Martin, B. J. (2015, August). *Muscle fatigue and discomfort associated with standing and walking: Comparison of work surfaces*. Paper presented at the 19th Triennial Congress of the International Ergonomics Association, Melbourne, Australia.

Bystrom, S., Mathiassen, S. E., & Fransson-Hall, C. (1991). Physiological effects of micropauses in isometric handgrip exercise. *European Journal of Applied Physiology and Occupational Physiology*, *63*, 405–411.

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

Chester, M. R., Rys, M. J., & Konz, S. A. (2002). Leg swelling, comfort and fatigue when sitting, standing, and sit/standing. *International Journal of Industrial Ergonomics*, *29*, 289–296.

Chiari, L., Rocchi, L., & Cappello, A. (2002). Stabilometric parameters are affected by anthropometry and foot placement. *Clinical Biomechanics*, *17*, 666–677.

Coenen, P., Parry, S., Willenberg, L., Shi, J., Romero, L., Blackwood, D., . . . Straker, L. (2017). Associations of prolonged standing with musculoskeletal symptoms: A systematic review of laboratory studies. *Gait & Posture*, *58*, 310–318.

Côté, J. N. (2014). Adaptations to neck/shoulder fatigue and injuries. In M. F. Levin (Ed.), *Progress in motor control* (Vol. 826, pp. 205–228). New York, NY: Springer.

Cote, J. N., Feldman, A. G., Mathieu, P. A., & Levin, M. F. (2008). Effects of fatigue on intermuscular coordination during repetitive hammering. *Motor Control*, *12*, 79–92.

Cowley, J. C., Dingwell, J. B., & Gates, D. H. (2014). Effects of local and widespread muscle fatigue on movement timing. *Experimental Brain Research*, *232*, 3939–3948.

de Rugy, A., Loeb, G. E., & Carroll, T. J. (2012). Muscle coordination is habitual rather than optimal. *Journal of Neuroscience*, *32*, 7384–7391.

Dingwell, J. B., Smallwood, R. F., & Cusumano, J. P. (2013). Trial-to-trial dynamics and learning in a generalized, redundant reaching task. *Journal of Neurophysiology*, *109*, 225–237.

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

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.

Eksioglu, M. (2006). Optimal work-rest cycles for an isometric intermittent gripping task as a function of force, posture and grip span. *Ergonomics*, *10*, 180–201.

Ferrari, M., Muthalib, M., & Quaresima, V. (2011). The use of near-infrared spectroscopy in understanding skeletal muscle physiology: Recent developments. *Philosophical Transactions*, *369*, 4577–4590.

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.

Gallagher, K. M., Campbell, T., & Callaghan, J. P. (2014). The influence of a seated break on prolonged standing induced low back pain development. *Ergonomics*, *57*, 555–562.

Gallagher, S., & Schall, M. C. J. (2017). Musculoskeletal disorders as a fatigue failure process: Evidence, implications and research needs. *Ergonomics*, *60*, 255–269.

Gandevia, S. C., Enoka, R. M., McComas, A. J., Stuart, D. G., & Thomas, C. K. (1995). Neurobiology of muscle fatigue. In S. C. Gandevia, R. M. Enoka, A. J. McComas, D. G. Stuart, & C. K. Thomas (Eds.), *Fatigue: Neural and muscular mechanisms* (pp. 515–526). New York, NY: Plenum Press.

Garcia, M. G., Graf, M., & Laubli, T. (2017). Lower limb pain among workers: A cross-sectional analysis of the fifth European Working Conditions Survey. *International Archives of Occupational and Environmental Health*, *90*, 575–585.

Garcia, M. G., Laubli, T., & Martin, B. J. (2015). Long-term muscle fatigue after standing work. *Human Factors*, *57*, 1162–1173. doi:10.1177/0018720815590293

Garcia, M. G., Wall, R., Steinhilber, B., Laubli, T., & Martin, B. J. (2016). Long-lasting changes in muscle twitch force during simulated work while standing or walking. *Human Factors*, *58*, 1117–1127. doi:10.1177/0018720816669444

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

Graf, M., Krieger, R., Läubli, T., & Martin, B. J. (2015, August). *Should we recommend people to stand more than sit at work?* Paper presented at the 19th Triennial Congress of the International Ergonomics Association, Melbourne, Australia.

Halim, I., Omar, A. R., Saman, A. M., & Othman, I. (2012). Assessment of muscle fatigue associated with prolonged standing in the workplace. *Safety and Health at Work*, *3*(1), 31–42. http://dx.doi.org/10.5491/SHAW.2012.3.1.31

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

Hepple, R. (2002). The role of O_2 supply in muscle fatigue. *Canadian Journal of Applied Physiology*, *27*, 56–69.

Hunter, S. K., & Enoka, R. M. (2003). Changes in muscle activation can prolong the endurance time of a submaximal isometric contraction in humans. *Journal of Applied Physiology*, *94*, 108–118.

Huysmans, M. A., Hoozemans, M. J. M., van der Beek, A. J., de Looze, M. P., & van Dieën, J. H. (2008). Fatigue effects on tracking performance and muscle activity. *Journal of Electromyography and Kinesiology*, *18*, 410–419. http://dx.doi.org/10.1016/j.jelekin.2006.11.003

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.

Karimi, Z., Allahyari, T., Azghani, M. R., & Khalkhali, H. R. (2016). Influence of unstable footwear on lower leg muscle activity, volume change and subjective discomfort during prolonged standing. *Applied Ergonomics*, *53*(Part A), 95–102.

Kim, J. H., & Johnson, P. W. (2014). Fatigue development in the finger flexor muscle differs between keyboard and mouse use. *European Journal of Applied Physiology*, *114*, 2469–2482.

Kuorinka, I., Jonsson, B., Kilbom, 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.

Lamb, G. D. (2002). Excitation-contraction coupling and fatigue mechanisms in skeletal muscle: Studies with mechanically skinned fibres. *Journal of Muscle Research and Cell Motility*, *23*, 81–91.

Lee, B. C., Thrasher, T. A., Layne, C. S., & Martin, B. J. (2016). Vibrotactile cuing revisited to reveal a possible challenge to sensorimotor adaptation. *Experimental Brain Research*, *234*, 3523–3530.

Lin, Y. H., Chen, C. Y., & Cho, M. H. (2012). Influence of shoe/floor conditions on lower leg circumference and subjective discomfort during prolonged standing. *Applied Ergonomics*, *43*, 965–970.

Madeleine, P., & Farina, D. (2008). Time to task failure in shoulder elevation is associated to increase in amplitude and to spatial heterogeneity of upper trapezius mechanomyographic signals. *European Journal of Applied Physiology*, *102*, 325–333.

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.

Maluf, K. S., Shinohara, M., Stephenson, J. L., & Enoka, R. M. (2005). Muscle activation and time to task failure differ with load type and contraction intensity for a human hand muscle. *Experimental Brain Research*, *167*, 165–177.

Maresh, C. M., Sokmen, B. F., Armstrong, L. E., Dias, J. C., Pryor, J. L., Creighton, B. C., . . . Kraemer, W. J. (2014). Repetitive

box lifting performance is impaired in a hot environment: Implications for altered work-rest cycles. *Journal of Occupational and Environmental Hygiene*, *11*, 460–468.

Mathiassen, S. E. (2006). Diversity and variation in biomechanical exposure: What is it, and why would we like to know? *Applied Ergonomics*, *37*, 419–427.

Mesin, L., & Farina, D. (2004). Simulation of surface EMG signals generated by muscle tissues with inhomogeneity due to fiber pinnation. *IEEE Transactions on Biomedical Engineering*, *51*, 1521–1529.

Messing, K., Tissot, F., & Stock, S. (2008). Distal lower-extremity pain and work postures in the Quebec population. *American Journal of Public Health*, *98*, 705–713. http://doi.org/10.2105/AJPH.2006.099317

Mudie, K. L., Gupta, A., Green, S., & Clothier, P. J. (2016). Adaptation of lower limb movement patterns when maintaining performance in the presence of muscle fatigue. *Human Movement Science*, *48*, 28–36.

Murthy, G., Kahan, N. J., Hargens, A. R., & Rempel, D. M. (1997). Forearm muscle oxygenation decreases with low levels of voluntary contraction. *Journal of Bone and Joint Surgery*, *15*, 507–511.

Oliveira, L. F., Simpson, D. M., & Nadal, J. (1996). Calculation of area of stabilometric signals using principal component analysis. *Physiological Measurement*, *17*, 305–312.

Ortenblad, N., Sjogaard, G., & Madsen, K. (2000). Impaired sarcoplasmic reticulum Ca(2+) release rate after fatiguing stimulation in rat skeletal muscle. *Journal of Applied Physiology*, *89*, 210–217.

Quaresima, V., Homma, S., Azuma, K., Shimizu, S., Chiarotti, F., Ferrari, M., & Kagaya, A. (2001). Calf and shin muscle oxygenation patterns and femoral artery blood flow during dynamic plantar flexion exercise in humans. *European Journal of Applied Physiology*, *84*, 387–394.

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

Ringheim, I., Austein, H., Indahl, A., & Roeleveld, K. (2015). Postural strategy and trunk muscle activation during prolonged standing in chronic low back pain patients. *Gait Posture*, *42*, 584–589. doi:10.1016/j.gaitpost.2015.09.008

Rudroff, T., Poston, B., Shin, I. S., Bojsen-Moller, J., & Enoka, R. M. (2005). Net excitation of the motor unit pool varies with load type during fatiguing contractions. *Muscle Nerve*, *31*, 78–87.

Schärli, A. M., van de Langenberg, R., Murer, K., & Müller, R. M. (2012). The influence of gaze behaviour on postural control from early childhood into adulthood. *Gait & Posture*, *36*, 78–84.

Sejersted, O. M., & Sjogaard, G. (2000). Dynamics and consequences of potassium shifts in skeletal muscle and heart during exercise. *Physiological Reviews*, *80*, 1411–1481.

Selen, L. P., Beek, P. J., & van Dieen, J. H. (2007). Fatigue-induced changes of impedance and performance in target tracking. *Experimental Brain Research*, *181*, 99–108.

Sjogaard, G. (1988). Muscle energy metabolism and electrolyte shifts during low-level prolonged static contraction in man. *Acta Physiologica Scandinavica*, *134*, 181–187.

Sjogaard, G., Savard, G., & Juel, C. (1988). Muscle blood flow during isometric activity and its relation to muscle fatigue. *European Journal of Applied Physiology*, *57*, 327–335.

Srinivasan, D., & Mathiassen, S. E. (2012). Motor variability in occupational health and performance. *Clinical Biomechanics*, *27*, 979–993.

Tabatabaeifar, S., Frost, P., Andersen, J. H., Jensen, L. D., Thomsen, J. F., & Svendsen, S. W. (2015). Varicose veins in the lower extremities in relation to occupational mechanical exposures: A longitudinal study. *Occupational and Environmental Medicine*, *72*, 330–337.

Tüchsen, F., Hannerz, H., Burr, H., & Krause, N. (2005). Prolonged standing at work and hospitalisation due to varicose veins: A 12 year prospective study of the Danish population. *Occupational and Environmental Medicine*, *62*, 847–850.

Uda, S., Seo, A., & Yoshinaga, F. (1997). Swell-preventing effect of intermittent exercise on lower leg during standing work. *Industrial Health*, *35*, 36–40.

Van Dieen, J. H., & Oude Vrielink, H. H. (1998). Evaluation of work-rest schedules with respect to the effects of postural workload in standing work. *Ergonomics*, *41*, 1832–1844.

Vieira, T. M., Loram, I. D., Muceli, S., Merletti, R., & Farina, D. (2011). Postural activation of the human medial gastrocnemius muscle: Are the muscle units spatially localised? *Journal of Physiology*, *589*, 431–443. doi:10.1113/jphysiol.2010.201806

Waters, T. R., & Dick, R. B. (2014). Evidence of health risks associated with prolonged standing at work and intervention effectiveness. *Rehabilitation Nursing*, *40*, 148–165.

Werner, R., Gell, N., Hartigan, A., Wiggermann, N., & Keyserling, W. (2010). Risk factors for foot and ankle disorders among assembly plant workers. *American Journal of Industrial Medicine*, *53*, 1233–1239.

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

Westerblad, H., Duty, S., & Allen, D. G. (1993). Intracellular calcium concentration during low-frequency fatigue in isolated single fibers of mouse skeletal muscle. *Journal of Applied Physiology*, *75*, 382–388.

Wiggermann, N., & Keyserling, W. M. (2013). Effects of anti-fatigue mats on perceived discomfort and weight-shifting during prolonged standing. *Human Factors*, *55*, 764–775.

Wood, D. D., Fisher, D. L., & Andres, R. O. (1997). Minimizing fatigue during repetitive jobs: Optimal work-rest schedules. *Human Factors*, *39*, 83–101.

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.

Zhang, L., Drury, C. G., & Woolley, S. (1992). Constrained standing: Evaluating the foot/floor interface. *Applied Ergonomics*, *23*, 215.

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