Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/terg20

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Published online: 21 Oct 2014.

To cite this article: Ming-Lun Lu, Laurel Kincl, Brian Lowe, Paul Succop & Amit Bhattacharya (2015) Muscular activity of lower limb muscles associated with working on inclined surfaces, Ergonomics, 58:2, 278-290, DOI: 10.1080/00140139.2014.968634

To link to this article: http://dx.doi.org/10.1080/00140139.2014.968634

Ergonomics, 2015
Vol. 58, No. 2, 278–290, http://dx.doi.org/10.1080/00140139.2014.968634

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(*Received 24 September 2013; accepted 15 September 2014*)

This study investigated the effects of visual cues, muscular fatigue, task performance and experience of working on inclined surfaces on activity of postural muscles in the lower limbs associated with maintaining balance on three inclined surfaces – 0°, 14° and 26°. Normalised electromyographic (NEMG) data were collected in 44 professional roofers bilaterally from the rectus femoris, biceps femoris, tibialii anterior and gastrocnemii medial muscle groups. The 50th and 95th percentile NEMG amplitudes were used as EMG variables. Results showed that inclination angle and task performance caused a significant increase in the NEMG amplitudes of all postural muscles. Visual cues were significantly associated with a decrease in the 95th percentile EMG amplitude for the right gastrocnemius medial and tibialis anterior. Fatigue was related to a significant decrease in the NEMG amplitude for the rectus femoris. Experience of working on inclined surfaces did not have a significant effect on the NEMG amplitude.

Practitioner Summary: Increasing angle of the working surface and task performance are two main factors contributing to muscular loading in the lower limb muscles. Input of visual cues while working on inclined surfaces may provide beneficial effects on reducing muscular loading to prevent occupational falls.

Keywords: EMG; postural stability; visual cues; fatigue; inclined surfaces

Introduction

According to the US Bureau of Labor Statistics (BLS), falls accounted for 12–15% of the total occupational fatal injuries every year from 2003 to 2011 (BLS 2003–2011). In 2008, fall-related events were the leading cause (total 35%) for median days away from work for non-fatal occupational injury (BLS 2008) and included falls to lower level (15%), falls on same level (10%) and slips, trips or loss of balance (10%). The Liberty Mutual Research Institute for Safety (2013) reported that falls on the same and to lower levels cost $13.5 billion in 2011, accounting for 24.3% of the total workers' compensation cost. In the same year, the fatal work injury rate among roofers (34.1 per 100,000 full-time equivalent workers) was almost 10 times as high as the average rate across all occupations (BLS 2013). In 2012, fatal injuries to roofers, primarily falls-related, rose to 70, a 17% rise from 2011 (BLS 2013). Clearly, the roofing industry has a work environment that compromises the workers' ability to maintain safe upright balance. However, causes of occupational falls from roofs are not fully understood (Dong et al. 2013).

A review (Hsiao and Simeonov 2001) on occupational fall protection identified many fall risk factors for roofers including inclined work surface, physical exertion, fatigue, task complexity, improper training and lack of protective equipment. The effects of the exposure to the workplace fall risk factors may be modified by workers' intrinsic factors, such as age and work experience (Gauchard et al. 2001). The intrinsic factors are mainly referred to as workers' ability to interact with the workplace or environmental factors to maintain safe upright balance (Gauchard et al. 2001). This interaction involves the central nervous system to perform a complex integration of the somatosensory, vestibular and visual input systems (Shumway-Cook and Woolacott 1995; Mezzarane and Kohn 2007). One of the input systems can be compensated partially or even fully by others (Vaughan, Davis, and O'Conner 1992). For example, if proprioceptive or vestibular input is compromised, additional demands will be placed on the visual system for maintaining safe upright balance (Vaughan, Davis, and O'Conner 1992).

Standing on inclined surfaces challenges the proprioceptive system by exposing ankle flexors and extensor muscles to different lengths (Mezzarane and Kohn 2007). In addition, the centre of gravity of the body is shifted to the boundary of the base of support while standing on an inclined surface. This biomechanical constraint further compromises the proprioceptive system for balance control. Recent studies demonstrated the destabilising effect of inclined surfaces on

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postural balance (Simeonov et al. 2003; Simeonov, Hsiao, and Hendricks 2009; Kincl et al. 2003). In the previous studies, availability of visual references was found to have a significant stabilising effect for maintaining upright balance on inclined surfaces (Simeonov, Hsiao, and Hendricks 2009; Kincl et al. 2003). However, this stabilising effect of visual references is unclear when other fall risk factors are present.

Among other fall risk factors, Kines (2002) indicated that fatigue was the contributing factor for fatal fall injury incidents because they predominantly occurred in the afternoon hours. Several previous studies report some evidence that muscular fatigue in the lower limbs may cause impaired postural control, which increases propensity for falls (Yaggie and McGregor 2002; Gribble and Hertel 2004; Mademli, Arampatzis, and Karamanidis 2008; Lin et al. 2009; Lin and Nussbaum 2012). Muscular fatigue of the lower limbs may affect body kinematics during a process of regaining balance (Mangharam 1998; Mangharam et al. 1999; Mademli, Arampatzis, and Karamanidis 2008) and gait parameters associated with slip propensity (Prakriti and Lockhart 2008). The affected body kinematics may be caused by interferences in joint proprioceptive sense or coordination of body movement that is essential for maintaining upright balance (Skinner et al. 1986; Forestier and Nougier 1998). Muscular fatigue may also interfere with the functioning of the central and peripheral nervous systems, both of which are required for maintaining balance (Astrand and Kaare 1977). However, the reported effects of muscular fatigue on maintaining upright balance on inclined surfaces are unclear.

Another unclear fall risk factor is work experience, although it has been identified in several previous studies as a potential fall risk factor in different workplaces (Prather, Crisera, and Fidell 1975; NIOSH 2000; Colak, Etiler, and Bicher 2004; Chi, Chang, and Ting 2005; Yeoh, Lockhart, and Wu 2013; Wade, Davis, and Weimar 2014). Experienced roofers have been found to underestimate fall risks, suggesting that the behaviours they routinely performed put them at greater risk of falling (Wade, Davis, and Weimar 2014). Other literature, however, contradicts this finding. Prather, Crisera, and Fidell (1975) reported that apprentice roofers had twice the injury rates of experienced roofers. The NIOSH study (2000) suggests that some of the fatal falls from inclined surfaces may be attributed to lack of experience and unfamiliarity with the work environment as nearly half of the fatal falls (total of 91 from 1982 to 1997) happened to workers who had less than 6 months of work experience. In Colak, Etiler, and Bicher's study (2004), the duration of employment was found to be the most important determinant of fall-related fatalities. In Chi, Chang, and Ting's (2005) study, inexperienced workers were found to be at greatest risk of fatal falls. As to underlying mechanisms explaining the effect of work experience on incidences of falling, the literature is lacking. Some preliminary finding suggests that work experience may mitigate age-related differences in balance control during surface accommodation (Rietdyk, McGlothlin, and Knezovich 2005). Research into how work experience mitigates fall risk factors while working on inclined surfaces may provide additional insights.

Task performance is considered another workplace fall risk factor, especially on elevated or inclined surfaces (Hsiao and Simeonov 2001; Wade, Davis, and Weimar 2014). Performance of different tasks has been used in previous laboratory-based studies to investigate the effect of locomotion for the tasks on perceiving loss of balance (Chiou, Bhattacharya, and Lai 2000) or maintaining upright balance on inclined surfaces (Kincl et al. 2003; Lay, Hass, and Gregor 2006; Lay et al. 2006). Injuries resulting from occupational falls have been linked to work types and tasks in the construction industry in some epidemiological work (Chau et al. 2004; Sa, Seo, and Choi 2009).

The combined effects of the aforementioned fall risk factors on maintaining upright balance have been investigated on flat or inclined surfaces typically using postural sway parameters (Bhattacharya et al. 1987, 1988; Seliga et al. 1991; Sack et al. 1993; Simeonov et al. 2003; Simeonov, Hsiao, and Hendricks 2009; Kincl et al. 2003). Posture sway data, however, cannot provide information on separate balance control mechanisms used by different posture muscles. Electromyographic (EMG) activity data have been used to provide insights into neural control strategies for locomotor tasks as well as maintaining upright balance using different postural muscles as a result of the integration of different sensory input challenges (De Luca 1985, 1997; Vuillerme, Nougier, and Teasdale 2002; Lay et al. 2006; Mezzarane and Kohn 2007; Sasagawa et al. 2009). Despite the valuable potential for understanding the role postural muscles play in response to fall risk factors, limited EMG data of postural muscles are available, especially for maintaining upright balance on inclined surfaces (Kluzik, Peterka, and Horak 2007; Mezzarane and Kohn 2007; Sasagawa et al. 2009). In these previous studies, small inclination angles were used (2.5–14°) and no multiple fall risk factors were investigated concurrently. To the authors' knowledge, only one relevant study (Lin and Nussbaum 2012) has been conducted to investigate the effect of muscle fatigue (i.e. a potential fall risk factor) on balance control while standing on steeper inclined surfaces (up to 26°). The goal of this previous study, however, was to examine the interactive effect of the lumbar extensor and inclination on balance control. No posture muscles in the lower limbs were tested in this previous study.

Workers' exposure to workplace fall risk factors is often coexisting (Hsiao and Simeonov 2001). The fall risk factors on inclined surfaces may be completely different from those found on level surfaces (Hsiao and Armstrong 2012). This study is designed to investigate the effects of the exposure to multiple fall risk factors on inclined surfaces that have been rarely examined. We hypothesise that the ability to maintain upright balance on inclined surfaces is regulated by the muscular activity of the lower limbs, which is affected by multiple workplace factors including inclination angle of working surface, availability of visual cues, type of work task, muscular fatigue of the lower limbs and experience of working on inclined surfaces. The purpose of the study is to explore the effects of the above-mentioned factors on the EMG activity of the lower limb postural muscles while maintaining upright balance.

Methods

Subjects

Forty-four subjects participated in the study. The subjects were recruited from roofing-related industries in the Greater Cincinnati area, Ohio, USA. They were interviewed on the phone using a standardised questionnaire to ensure that they did not have balance-related diseases that might interfere with the study results. If they met the inclusion criteria, and upon medical approval by a physician after examination, the subjects were eligible to participate in this study and signed a consent form. The experimental protocol was approved by the University of Cincinnati's Institutional Review Board for Human Research. Subjects working on inclined surfaces for less than 1 year were categorised as inexperienced and with more than 3 years were categorised as experienced workers. The demographic information of the subjects by experience group is summarised in Table 1. Student *t*-tests revealed that there was no significantly statistical difference ($p < 0.05$) in weight, body mass index and age between the experienced and inexperienced workers.

Experimental design

Inclination angle of work surface (0°, 14° and 26°), task type (stationary/reach), fatiguing level (none, half and full) and visual cue input (yes/no) were used as the independent variables for a total of 36 test combinations of the variables. The EMG activity of eight postural muscles was used as the dependent variable in this article. We used a split-plot design with inclination angles as whole plots and the remainder of the independent variable as split plots. To avoid non-experimental fatigue in the postural muscles due to a long test session, the 36 test conditions were divided into four separate test sessions, with at least one day of rest between sessions. Nine experimental tests and one baseline test were conducted in each session. The baseline test was performed in the beginning of each session to calibrate a force platform used for postural balance testing (Kincl et al. 2003). The inclination angle was first randomised, followed by complete randomisation of the test conditions within each inclination angle. Because the test conditions were blocked by inclination, 12 tests on the same inclination were to be performed across two sections, with a total of four sessions to complete all three inclination levels. For example, the first session had nine test conditions on one inclined surface. The second session had the remaining three tests on the same inclination used in the first session and six tests on a different inclination. The third session had the six remaining tests on the different inclination used in the second session and three tests on the third inclination. The remaining nine tests on the third inclination were completed in the fourth session. To minimise potential session effects, the four above-mentioned sessions were randomly assigned to each subject.

Inclined surfaces

Three surface inclination angles (0°, 14° and 26°) were chosen to correspond to roof pitches that are commonly used in construction sites (Johnson 1976). The inclined surfaces were made of cast iron and sand-blasted for a safer grip while standing. An aluminium plate with connectors on each corner was placed directly on top of a force platform (AMTI model OR6-5-1000, Boston, MA, USA) and the incline structure was then attached to the aluminium plate (Figure 1).

Task type

Stationary and forward reach tasks were performed. The stationary task was an upright standing posture. The reach task simulated dynamic forward lifting and movement, such as lifting a shingle. For the stationary task, the subjects stood upright quietly for 30 seconds. For the reach task, the subjects reached forward to pick up a wooden bar (2.2 kg) resting at arm's length in front of them at waist height and brought in to their waist when the tester gave the subjects a verbal

Table 1. Demographics of the subjects, grouped by work experience (experienced: >3 years; inexperienced: <1 year).

Subject group	N	Weight (kg)	Height* (cm)	BMI (kg/cm^2)	Age (years)
Inexperienced	28	83.9 ± 20.6	169.8 ± 8.56	29.2 ± 6.8	38.0 ± 10.8
Experienced	16	90.1 ± 13.5	177.9 ± 6.6	28.9 ± 4.7	42.8 ± 9.1

Note: Data are mean ± standard deviation. BMI, body mass index. *Significantly different between two groups ($p < 0.05$).

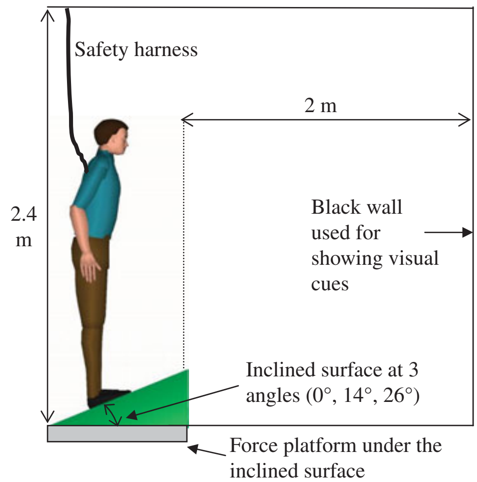

Figure 1. Schematic layout of the experimental set-up.

command 'start' in the 8th second of the 30-second test. The subjects performed four cycles of the reach task and then resumed the initial standing position for the remainder of the test. Approximately 10 seconds were used for performing the reach task during each 30-second trial. The 2.2 kg weight was chosen to minimise the effect of loading on the back and other body parts.

Fatiguing task

To produce effects of fatigue in the eight postural muscles 'simultaneously', the subjects sustained a semi-squat position (Wickstrom, Bhattacharya, and Shukla 1988; Pippinger et al. 1994; Mangharam et al. 1999). Failure of the postural muscles to maintain the semi-squat position was considered a fatigue in this study (Chaffin 1973). During the squat, subjects turned a small object (5 g) on the Minnesota Manual Dexterity Testing Board, which was used to draw the subjects' attention. To standardise the semi-squatting position, the board was placed in front of the subjects at their functional reach distance (i.e. arm length) and knee height. The position was marked by tape at their waist. The standardised semi-squatting position was monitored by the tester according to the mark during each fatiguing task to assure compliance. The longest time that each subject could voluntarily maintain the semi-squat position was recorded as his/her maximum fatiguing period and the completion of the fatiguing task was defined as the full fatiguing task (Corlett and Bishop 1976). The half fatiguing task was defined as the completion one half of the maximum fatiguing period. For the no-fatigue task, the subjects rested on a chair until their heart rate stabilised to resting. The resting heart rate was established by the subjects' radial pulse rate, which was taken seven times with an interval of 2 minutes between two consecutive measurements while the subject was sitting quietly. The average of the seven readings was calculated as the resting heart rate.

Visual cues

Two visual cue conditions (with or without the visual cues) were used. A previous study conducted in our laboratory has shown that H-shaped visual cues in the central and peripheral fields can reduce subjects' postural instability (Bhattacharya et al. 2003). The H-shaped cues were used in this study and consisted of one horizontal cue with a vertical cue on either side of the horizontal cue. These cues were made from phosphorescent strips and were 10 cm × 300 cm in size that were luminous when the lighting was poor (< 20 lux). Without the visual cues, the subjects simply stood on the force platform and looked forward in a black enclosure where the environmental lighting was simulated as the level of dusk/dawn conditions (< 20 lux). The distance between the visual cues and the subjects' eyes was approximately 2 m (Figure 1).

EMG instrumentation

An 8 channel Paromed data logger telemetric EMG recorder (Paromed Inc., Neubeuern, Germany) was used to measure the EMG signal eight postural muscles: left rectus femoris (LRF), right rectus femoris (RRF), left biceps femoris (LBF), right biceps femoris (RBF), left tibialis anterior (LTA), right tibialis anterior (RTA), left gastrocnemius medial (LGM) and right gastrocnemius medial (RGM). Data collection at a sampling rate of 1000 Hz was triggered by remote control with a transmitting frequency of 72 MHz. Bipolar surface Ag/AgCl electrodes were superficially placed on the belly of each muscle 4 cm apart at standard positions (Delagi et al. 1981; Bhattacharya and Ramakrishanan 1986; Soderberg 1992). To increase the reliability of the EMG measurements between sessions, the temperatures in the test room were set at 70°F for all sessions and the standardised locations of the electrodes were marked on the subject's skin for the following sessions. The collected EMG data were processed and filtered in a band of 30–350 Hz by a finite impulse response filter with Lanczos smoothing using the Datapac 2000 version 2.00j software (Run Technologies, Laguna Hills, CA, USA). The data were further processed by the root mean square method with a time constant of 50 milliseconds (NIOSH 1992).

Testing procedure

To compare EMG results across muscle groups and subjects, a normalisation technique was employed. Previous studies indicate that EMG activity normalised to single angle maximum voluntary contraction (MVC) in the lower limbs for various ranges of ankle and knee motion have been found to provide similar results to angle-specific EMG normalisation (Knudson and Johnston 1993; Burden, Trew, and Baltzopolopus 2003; Gallagher, Pollard, and Porter 2011). Knudson and Johnston (1993) even argued that the traditional single-angle EMG normalisation may be more appropriate for studies of patterns of muscle activation. To obtain normalised EMG (NEMG) data for this study, an MVC test for each postural muscle at a specific angle was performed (Ericson et al. 1985; Bhattacharya and Ramakrishanan 1986). A plinth was set up for the subjects to sit/lie to measure the various muscle groups' MVC. During the MVC test, a 90° knee flexion angle was maintained for the RF and BF in a sitting position, while a 90° ankle flexion was maintained for the TA and GM in a supine position on a physical examination table (Manghram et al. 1998). Two columns of angle irons (for the right and left side of the body) were bolted to the wall at one end of the plinth to attach the load cell (Jackson Evaluation System, model 32528; serial 280256) and cable leading to the subjects' ankle or foot perpendicular to the wall. The load cell height was adjustable up and down the angle irons to ensure that the load cell was set to measure the perpendicular force exerted by the muscle group (i.e. the subject was pulling or pushing perpendicularly from the wall). During the MVC test, the subjects were instructed to flex their ankle or knee maximally for 3 seconds. The maximal signal recorded during this period was used as the MVC EMG data.

Resting EMG signal was recorded for each muscle group before the MVC test and before the first test during the following separate test sessions. For recording the resting EMG, the subjects were relaxed in the standardised sitting position with their legs relaxed for approximately 10–15 minutes to allow themselves to be fully rested (indicated by their resting heart rate). The measurements in the interval between first and fourth second of a 30 second recording period were used as the resting EMG data (Manghram et al. 1998).

Prior to the first test in each session, the subjects were seated with their legs in a relaxed position (standardised resting position) for approximately 10–15 minutes to allow themselves to be fully rested, as indicated by their resting heart rate. A baseline test was performed for checking the function of the force platform. After the baseline test and the subjects reached their resting heart rate in the standardised resting position, they performed a randomly assigned test condition starting with the fatiguing test (none, half or full). Immediately after completion of the fatiguing task, the subjects stood in a standardised position (feet apart approximately at the shoulder width) marked with a footprint on the surface (0°, 14° or 26° inclination) and relaxed their hands on their hips. The subjects stood on the surface for 30 seconds performing one of the two tasks with one of the two visual cue settings. After the test, the subjects rested in the standardised resting position for approximately 2–5 minutes until they were rested for the next test condition, as indicated by their resting heart rate.

EMG variables

The average of the maximum of three MVC trials was calculated as the subject's MVC EMG signal for the muscle and used in the following formula to calculate the NEMG (Mirka 1991; NIOSH 1992):

$$\text{NEMG}(\,\%\text{MVG}) = \frac{\text{Trial EMG signal} - \text{resting EMG signal}}{\text{MVG EMG signal} - \text{resting EMG signal}}.$$

The amplitude probability density function (APDF) (Jonsson 1988) for the time-history NEMG of each muscle and each trial were generated using custom software developed with Labview, Version 5.1 (National Instruments, Austin, TX, USA). The cumulative APDF provides a meaning of the muscular activity being lower than or equal to a specific level of the % MVC (Hagberg 1979). The NEMG at the 50th and 95th %MVC ($\%\text{MVC}_{50\text{th}}$ and $\%\text{MVC}_{95\text{th}}$) were calculated from the cumulative APDF curve for each muscle and each trial (Jonsson 1988). Due to potential spike artefacts, the $\%\text{MVC}_{95\text{th}}$ provides a more reliable EMG measure than the maximum of the EMG activity levels and the $\%\text{MVC}_{50\text{th}}$ provides a more reliable EMG measure as compared with mean. These measures have been used in a number of studies and shown to be stable indicators for measuring EMG activity levels (Hagberg 1979; Jonsson 1988; Aaras and Ro 1997; Gerard et al. 2002).

Statistical analysis

An analysis of variance (ANOVA) was used to determine the effects of the experimental conditions on the NEMG variables (%MVC_{50th} and %MVC_{95th}). The log transformation was applied to attempt to normalise the residuals. The four main experimental conditions (inclination angle, fatiguing level, task type and visual cue input) and work experience were included in each model and tested for statistical significance ($p < 0.05$) on the NEMG variables. The work experience, a subject attribute, was considered a fixed blocking variable in each model. Although the test session effect would have been minimised by randomisation of the test sessions for each inclination angle, a variable session (two nominal values for each inclination angle) was used to evaluate the potential session effect. A total of 16 models were performed separately for each EMG variable of each muscle. The Personal Statistical Analysis System (SAS) version 8.01 (SAS Institute Inc., Cary, NC, USA) was used to perform the statistical analysis.

Results

Left and right postural muscles exhibited similar NEMG patterns and amplitudes in response to the test conditions. Therefore, the general patterns and amplitudes of the NEMG activity of the postural muscles are presented by the mean values of the NEMG variables for the right and left postural muscles in Figure 2. Figure 2(A),(B), respectively, presents the geometric mean of the %MVC_{50th} and %MVC_{95th} of each postural muscle as a function of inclination angle and task type. Visual cues and fatigue did not significantly affect most NEMG variables and therefore the NEMG variables in Figure 2 are summarised across the two test conditions.

The %MVC_{50th} of most postural muscles, except TA, was smaller than 10% (11.4% for the TA) for all test conditions. Both %MVC_{50th} and %MVC_{95th} of the TA increased as the inclination angle increased from 0° to 26° and exhibited a statistically significant increase for both stationary and reach tasks from 14° to 26° inclination angle. The %MVC_{95th} of the TA increased to 31% and 36% for the stationary and reach tasks on the 26° inclination, respectively. The increases in the %MVC_{95th} of the TA were approximately 16 and 12.4 times greater than the NEMG level for the stationary and reach tasks on 0° inclination, respectively. Both %MVC_{50th} and %MVC_{95th} of the TA for both tasks on the 26° inclination exhibited the greatest level among all postural muscles.

The %MVC_{50th} and %MVC_{95th} of the GM were the greatest among all postural muscles for both stationary and reach tasks on the 0° and 14° inclinations, and were the second greatest for both tasks on the 26° inclination. The NEMG amplitude of the GM, especially the %MVC_{95th}, was significantly affected by the reach task. The %MVC_{95th} of the GM for the reach task on the 0°, 14° and 26° inclinations were 21%, 22% and 30%, respectively, which were three to four times greater than those for the stationary task on the respective inclinations. The inclination angle had little effect on the %MVC_{95th} of the GM, as indicated by the similar NEMG levels across the three inclination angles.

The %MVC_{50th} of the biceps femoris (BF) for both stationary and reach tasks on the three inclinations were below 3%. The %MVC_{95th} of the BF for the reach task on the 0°, 14° and 26° inclinations were 11.2%, 10.9% and 12.7%, respectively, which were significantly greater than those (all $<5\%$) for the stationary task on the respective inclinations. As the inclination angle increased, the NEMG amplitude of the BF increased. However, the increases in the NEMG amplitude of the BF were not as drastic as the TA.

The %MVC_{95th} and %MVC_{50th} of the rectus femoris (RF) were small for all test conditions. The means of the %MVC_{50th} and %MVC_{95th} of the RF for the three inclinations ranged from 1.8% to 3.3% and 4% to 7.6%, respectively. As the inclination angle increased from 0° to 26°, the %MVC_{95th} and %MVC_{50th} of the RF increased slightly. It appeared that among the NEMG activity of all the postural muscles for the test conditions, the RF had the least responses.

Table 2 summarises the results from the 16 final ANOVA models. The effect of test session ($p = 0.11$–0.98 for the %MVC_{95th} and $p = 0.55$–0.97 for the %MVC_{50th}) was not significantly associated with any EMG measures and therefore the session variable was removed from the final models. Inclination had a significant effect ($p < 0.05$) on all the NEMG variables except the %MVC_{95th} of the LBF. Task was significantly ($p < 0.05$) associated with the %MVC_{95th} of all postural muscles and the %MVC_{50th} of all postural muscles except the RF. Visual cues were significantly ($p < 0.05$) associated with a decrease in the %MVC_{95th} of the RTA and RGM, and had a borderline significant effect on the %MVC_{50th} of the LBF ($p = 0.06$), the %MVC_{95th} of the LTA ($p = 0.06$) and the %MVC_{50th} of the RGM ($p = 0.07$). Effects of fatigue were significantly ($p < 0.05$) associated with the %MVC_{95th} of the LRF, the %MVC_{50th} of the LRF and RRF, and the %MVC_{95th} of the RGM. In addition, fatigue had a borderline significant effect on the %MVC_{95th} of the RRF ($p = 0.09$) and the LBF ($p = 0.08$), respectively. To further present the effects of fatigue on the NEMG variables of the RF, Table 3 shows the least

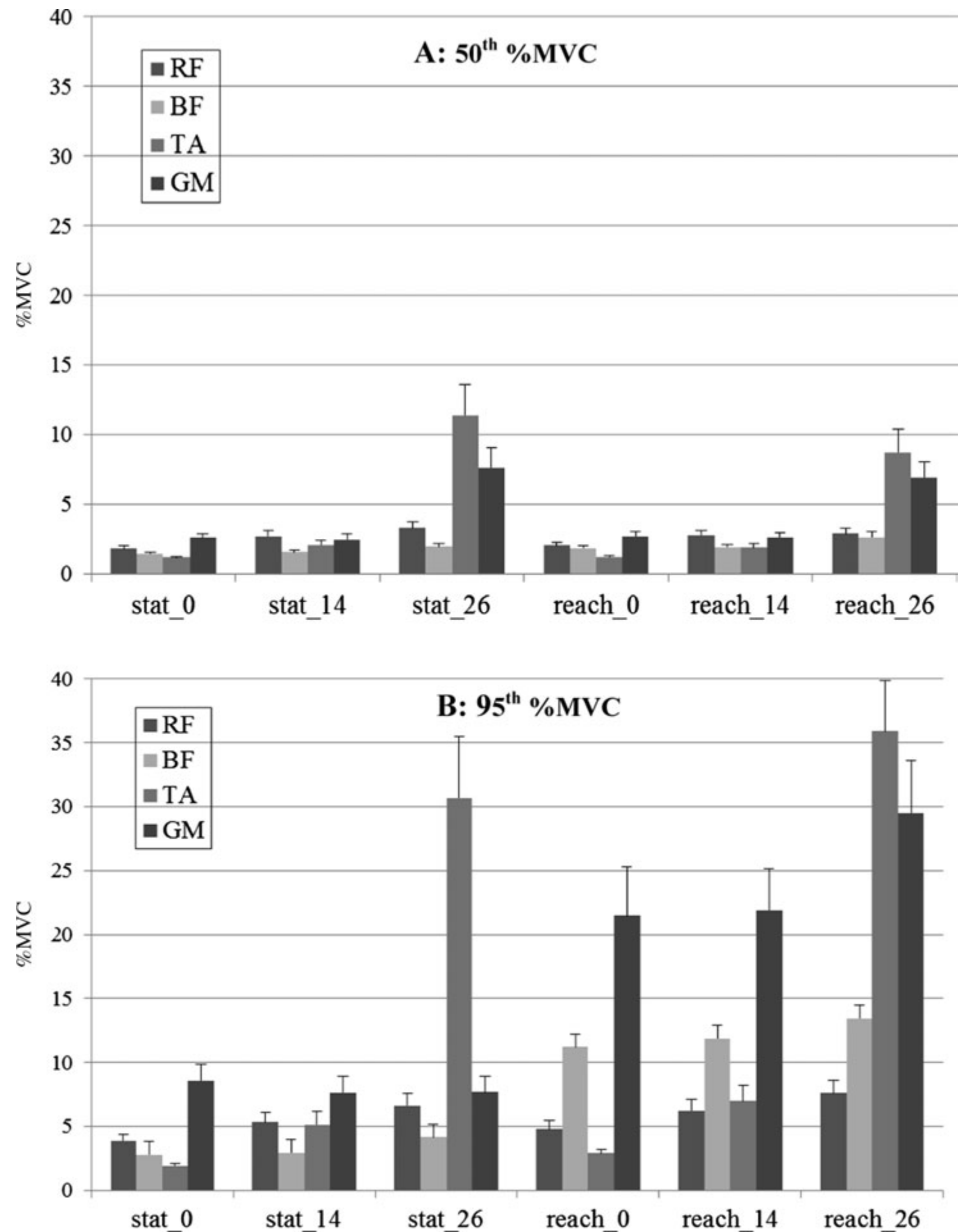

Figure 2. Geometric means (+ error bars) for the 50th (A) and the 95th (B) percentile NEMG amplitudes of bilateral postural muscles as a function of inclination angle and task type (RF: rectus femoris; BF: biceps femoris; TA: tibialii anterior; GM: gastrocnemii medial). Stat_0, stat_14 and stat_26 represent performing the stationary task on 0°, 14° and 26° inclinations, while reach_0, reach_14 and reach_26 represent performing the reach task on 0°, 14° and 26° inclinations.

square means (LSM) for the $\%MVC_{50th}$ and $\%MVC_{95th}$ of the LRF and RRF by the three levels of fatigue. It is worth noting that as the level of fatigue increased, the LSM for the NEMG variables of the RF decreased. Experience of working on inclined surfaces was not found to have a significant effect ($p < 0.05$) on any of the EMG variables.

Discussion

To our knowledge, this is the first study to examine the combined effects of several workplace fall risk factors (task performance, visual cue input, muscular fatigue and work experience) on the muscular activity of eight postural muscle groups in the lower limbs for maintaining upright balance on inclined surfaces. Among the experimental factors, task and inclination were the two major factors affecting the NEMG amplitudes of the postural muscles.

Table 2. Effects of the experimental conditions on the 50th and 95th percentile NEMG amplitudes of the postural muscles.

		Postural muscles							
Experimental conditions	NEMG amplitude percentile	LRF	RRF	LBF	RBF	LTA	RTA	LGM	RGM
Fatigue	95th	A	B	B	C	C	C	C	A
	50th	A	A	C	C	C	C	C	C
Task	95th	A	A	A	A	A	A	A	A
	50th	C	C	A	A	A	A	A	A
Cues	95th	C	C	C	C	B	A	C	A
	50th	C	C	B	C	C	C	C	B
Incline	95th	A	A	C	A	A	A	A	A
	50th	A	A	A	A	A	A	A	A

Note: A, statistically significant ($p < 0.05$); B, borderline significant ($p = 0.05$–0.1); C, not significant ($p > 0.1$).

Table 3. LSM for the 50th and 95th percentile EMG amplitudes of the LRF and RRF between three levels of fatigue.

	$\%MVC_{50th}$		$\%MVC_{95th}$	
Fatigue level	LRF*	RRF*	LRF*	RRF**
No	0.9	0.97	1.7	1.8
Half	0.85	0.9	1.64	1.73
Full	0.8	0.83	1.59	1.69

Note: *Statistically significant ($p < 0.05$); **borderline statistically significant ($p < 0.09$).

Effect of inclination angle

The study findings suggest that minimal muscular activity (<5% MVC for $\%MVC_{50th}$ and <7% MVC for the $\%MVC_{95th}$) of the RF and BF was required for maintaining upright balance while standing on the three inclinations. Increasing angles of the inclination primarily activated the contractions of the TA, leading to a 16-fold increase (1.9–30.7% MVC) in the $\%MVC_{95th}$ of the TA from 0° to 26° inclination. The significant increase in the muscular activity of the TA was likely caused by a combination of passive dorsiflexion of the ankles and active muscle contractions for maintaining upright balance on the inclinations. The TA is the main dorsal ankle flexor, and its contractions with the antagonist GA increase the ankle stiffness to maintain upright balance (Blanchet, Marchand, and Cadoret 2012; Winter et al. 1998). Increased muscular activity of the TA suggests a difficulty to maintain upright balance on an inclined surface (Blanchet et al. 2012). The large amplitudes of the muscular activity of the TA while standing on the inclined surfaces (up to a 30.7% of $\%MVC_{95th}$ for standing on the 26° inclination) also suggest a potential risk for muscular fatigue.

Effect of task type

Because of the design of the tasks, the NEMG amplitudes of the postural muscles for the reach task were seemingly greater than the stationary task. Upon a closer examination, however, the reach task primarily caused increased muscular activity of the posterior postural muscle (GM and BF) and had limited effects on the anterior postural muscles (RF and TA). The increased contractions of the GM and BF were probably attributed to the muscular efforts to create additional stiffness of the ankles and knees to counter the destabilising torque in the forward direction for performing the reach task. Approximately a two- to threefold increase in the $\%MVC_{95th}$ of the GM and BF was found for performing the reach task, compared with that required for standing on the inclined surfaces. It should be noted that there was no significant increase in the $\%MVC_{50th}$ of the GM and BF for the reach task because the EMG measure represented the medium of the time-history NEMG signal that occurred outside the time period (about 10 seconds) of performing the reach task during the 30-second trial.

Effect of fatigue

Primarily, fatigue had a significant effect on the NEMG activity of the RF. As the level of fatigue increased, the NEMG amplitude of the RF decreased. The decreasing trend in the NEMG amplitude indicates that the cumulative APDF curve for the NEMG shifted towards left (i.e. lower activity levels), which contradicts the previous research findings that muscular fatigue caused a shift of the APDF curve to the right (Hagberg 1979; Jonsson 1988). This contradictory finding might be explained by the following three reasons. First, quantifications of muscle activity less than 10% MVC using EMG analysis may be less reliable (NIOSH 1992). Exertions of the RF during the tests were generally low (< 10% MVC in all conditions), which might not have produced a clear manifestation of fatigue by the EMG analysis. Second, the subjects may have used different postural muscle groups for maintaining upright balance after the RF had been fatigued. Substitution of other adjacent muscle groups for the fatigued muscle is a common phenomenon and might exist in the subjects of this study, although this explanation might be speculative. Third, due to adjustments of hip movements to maintain balance during the postural balance tests, the length of the RF might have changed. Changes in muscle length have a significant effect on the EMG signal (Okada 1987; Arendt-Hielsen, Gantchew, and Sinkjaer 1992; Doud and Walsh 1995). The potential for changes in muscle length during the postural balance tests might have caused the unexpected effects on the decreased EMG activity of the RF.

Effect of visual cues

We hypothesise that a lack of visual cues would trigger an increase in the EMG activity of the postural muscles as a compensatory response to maintain balance with only two remaining afferents (i.e. vestibular and proprioceptor systems) (Vaughan, Davis, and O'Conner 1992). The statistically significant and borderline significant results on the NEMG activity of four postural muscles (LTA, RTA, LBF and RGM) provide some evidence for the hypothesis. That is, the presence of the H-shaped visual cues may have an effect on a decrease in the NEMG activity of some postural muscles. It should be noted that in a multi-factor ANOVA design, the effect of one factor (in this case, visual cues) may be suppressed by other factors (in this case, reach task and inclination) that do not require a larger sample size to find their significant effects. The effect of visual cues on the NEMG activity of the postural muscles should be further studied with a larger sample size, if strong factors such as inclination angle and task performance are to be evaluated together.

Visual reference has been known to be a major stabilising factor for postural balance on flat (Bhattacharya et al. 1987, 1988; Seliga et al. 1991; Sack et al. 1993; Wang 1996; Chiou et al. 1998) and inclined surfaces (Simeonov, Hsiao, and Hendricks 2009; Kincl et al. 2003). The H-shaped visual cues used in this study were associated with a stabilising effect on postural stability on inclined surfaces (Kincl, Bhattacharya, and Succop 2002; Bhattacharya et al. 2003). Because input of visual cues has been shown to have a significant effect on postural balance measures with a similar sample size and the same experimental setting in some previous studies (Chiou et al. 1998; Bhattacharya et al. 2003), it appears that the EMG measures used in this study are not as sensitive as the balance stability measures used in the previous studies.

Effect of work experience

The results of this study showed that experience of working on inclined surfaces was not associated with the NEMG activity of the postural muscles. The muscular responses to postural instability on the inclined surfaces may be pre-programmed in the central nervous system based on learning and past experience, and not on a conscious decision made at the time of response (Shumway-Cook and Wollacott 1995). The ability to maintain upright balance depends on the task conditions and the person's experience (Nashner 1993). In this study, the subjects without experience of working on inclined surfaces might have experienced postural instability on inclined surfaces in non-working environments and learned how to maintain balance on the inclined surfaces, as experienced workers did. In other words, such learned ability to maintain upright balance might have coexisted in the subjects with and without experience of working on inclined surfaces, resulting in similar muscular responses to the test conditions. In addition, the inconclusive effect of the work experience factor on the NEMG activity may be attributed to the definition of work experience. The defined work experience of > 3 years as experienced workers might be insufficient to discriminate differences in the two experience groups. Furthermore, it is also likely that the test conditions did not perturb the subjects' balance enough to cause a significant difference in the EMG activity of the posture muscles between the experienced and inexperienced workers.

Limitations

The defined fatigue in this study solely relied on subjects' psychophysical tolerance for sustaining the fatiguing task. The tolerance time for the fatiguing task (i.e. voluntarily maintaining the semi-squat position as long as possible) might not be sufficient to produce 'true' fatigue in all muscles, because the time required for the onset of fatigue for each muscle group might vary. Varying results regarding the effect of muscular fatigue on EMG measurements exist, in large part depending on the muscle recruited and the method used for evaluations (Lin et al. 2009). Different fatiguing protocols to further examine the effect of muscular fatigue on the posture muscles for maintaining upright balance on inclined surfaces are recommended.

A poor lighting condition (<20 lux) was used in this study to simulate the effect of the visual cue setting in dawn/dusk lighting conditions, in which visual input used for maintaining balance is most compromised. The effect of the same visual cue setting in regular daylight conditions is unknown. Moreover, the placement of the H-shaped visual cues in the workplace may not be practically feasible. Nevertheless, this study provides some insights into the effects of visual cues on postural muscle loading for maintaining upright balance while working on inclined surfaces.

The effect of two test sessions for the same inclination on the EMG measurements may raise a concern about the reliability of the between-session EMG data. The reliability issue depends on the experimental set-up and type of muscle examined (Knutson et al. 1994). Our statistical analysis did not reveal a significant session effect, which was likely to be attributed to the control strategies (standardised electrode location, temperature control and randomisation of test sessions) implemented in the study. Despite the non-significant statistical results, between-session variations might not have been controlled completely in this study. Caution should be exercised when interpreting the study findings related to the effect of inclination.

Criticism may arise as to the inflated Type 1 errors attributed to the unadjusted alpha level for testing a statistical significance of the eight dependent measures. After adjusting the alpha level by the Bonferroni correction, the significant effects of the task and inclination remained, while the significant effects of fatigue and visual cue setting were removed (data not shown). It is not surprising because the significant effects of fatigue and visual cue setting were not found on the majority of the EMG measures without the adjustment and the chances of having the true effects were not as probable (i.e. smaller p values) as task and inclination, both of which exhibited an unadjusted p value < 0.0001. Because of the exploratory nature of the study, findings based on the unadjusted alpha level are generally acceptable. Readers, however, should keep this potential error in mind.

Conclusions

Some conclusions from the study are drawn as follows:

1. Increased inclination angle and task performance were significantly associated with NEMG activity of the lower limb postural muscles, especially the TA. The finding suggests that working on inclined surfaces may be prone to developing muscular fatigue, especially in the TA, if working for prolonged periods of time.
2. Input of visual cues while working on inclined surfaces may provide beneficial effects on reducing the muscular loading for preventing occupational falls.
3. Effects of work experience and muscular fatigue on the postural muscles were unclear. Research into different muscular fatiguing protocols and work experience definitions may help elucidate the effects.

Acknowledgements

The authors gratefully thank Terry Mitchell, Cyndy Cox, Jessica Gordon, Ed Auyang, Mary Lin, Allen Wang, Jean Mangharam, Yu Ning, Sachin Abhyankar and Jian Huang for their contribution in data collection.

Funding

The funding for this study was provided by the National Institute for Occupational Safety and Health [grant number R01-OH03400].

Disclaimer

The findings and conclusions in this study are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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