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Muscular activity of lower limb muscles associated with working on inclined surfaces

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Abstract

This study investigated 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°. Normalized electromyographic (NEMG) data were collected on 44 professional roofers bilaterally from the rectus femoris, biceps femoris, tibialii anterior, and gastrocnemii medial muscle groups. The 50th and 95th percentile normalized EMG 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.

Keywords

EMG; Postural stability; Visual cues; Fatigue; Inclined surfaces

Introduction

According to the United States Bureau of Labor Statistics (BLS), falls accounted for 12–15% of the total occupational fatal injuries every year from 2003 to 2011 (BLS, 2003–

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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, 1995; Mezzarane and Kohn, 2007). One of the input systems can be compensated partially or even fully by the others (Vaughan, 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, 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 center 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 destabilizing effect of inclined surfaces on postural balance (Simeonov et al., 2003, 2009; Kincl et al., 2003). In the previous studies, availability of visual references was found to have a significant stabilizing effect for maintaining upright balance on inclined surfaces (Simeonov et al., 2009; Kincl et al., 2003). However, this stabilizing 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 et al., 2004; Mademli et al., 2008; Lin et al., 2009, 2012). Muscular fatigue of the lower limbs may affect body kinematics during a process of regaining balance (Mangharam 1998, 1999; Mademli et al., 2008) and gait parameters associated with slip propensity (Parijat 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, 1986; Forestier et al. 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, 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 et al., 1975; NIOSH, 2000; Colak, et al., 2004; Chi, C. et al., 2005; Yeoh et al., 2013; Wade et al., 2014). Experienced roofers have been found to underestimate fall risks, suggesting that the behaviors they routinely performed put them at greater risk of falling (Wade et al., 2014). Other literature, however, contradicts with this finding. Prather et al. (1975) reported that apprentice roofers had twice the injury rates of experience 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 1982–1997) happened to workers who had less than 6 months of work experience. In Colak et al.'s study (2004), the duration of employment was found to be the most important determinant of fall-related fatalities. In Chi et al.'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 et al., 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 (Hsaio Simeonov, 2001; Wade et al., 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 et al., 2000) or maintaining upright balance on incline surfaces (Kincl et al., 2003; 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 et al., 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; Chiou, Bhattacharya et al,. 2003; Simeonov et al., 2003, 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; Vuilerme et al. 2002; Lay et al., 2007; Mezzarane and Kohn, 2007; Sasagawa et al., 2009). Despite the valuable potential for understanding the role of 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 et al., 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 than those found on level surfaces (Hsiao and Armstrong, 2012). The present study is designed to investigate the effects of the exposure to multiple fall risk factors on inclined surfaces that have been rarely examined. We hypothesize 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, United States. They were interviewed on the phone using a standardized 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 one year were categorized as inexperienced and with more than three years were categorized as experienced workers. The demographic information of the subjects by experience group is summarized in Table 1. Student t-tests revealed that there was no significantly statistical difference ($P<0.05$) in weight, body mass index (BMI) 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 the current paper. 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 randomized, followed by complete randomization 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 4 sessions to complete all three inclination levels. For example, the first session had 9 test conditions on 1 inclined surface. The second session had the remaining 3 tests on the same inclination used in the first session and 6 tests on a different inclination. The third session had the 6 remaining tests on the different inclination used in the second session and 3 tests on the third inclination. The remaining 9 tests on the third inclination were completed in the fourth session. To minimize 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 aluminum plate with connectors on each corner was placed directly on top of a force platform (AMTI model OR6-5–1000, Boston, MA) and the incline structure was then attached to the aluminum 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 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-sec trial. The 2.2 kg weight was chosen to minimize the effect of loading on the back and other body parts.

Fatiguing task

To produce effects of fatigue in the 8 postural muscles “simultaneously”, the subjects sustained a semi-squat position (Wickstrom, Bhattacharya & Shukla, 1988; Pippinger, 1994; Mangrham, Bhattacharya, Succop & Bagchee, 1999). Failure of the postural muscles to maintain the semi-squat position was considered a fatigue in the present study (Chaffin 1973). During the squat, subjects turned a small object (5g) on the Minnesota Manual Dexterity Testing Board, which was used to draw the subjects’ attention. To standardize 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 standardized 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 & 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 stabilized to resting. The resting heart rate was established by the subjects' radial pulse rate, which was taken 7 times in an interval of 2 minutes between two consecutive measurements while the subject was sitting quietly. The average of the 7 readings was calculated as the resting heart rate.

Visual cues

Two visual cues 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 the present study and consisted of one horizontal cue with a vertical cue at 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 (PDL) telemetric EMG recorder (Paromed Inc, Germany) was used to measure the EMG signal 8 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 Ramakrishanah, 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 standardized 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). The data were further processed by the root mean square (RMS) method with a time constant of 50 msec (NIOSH, 1992).

Testing procedure

To compare EMG results across muscle groups and subjects, a normalization technique was employed. Previous studies indicate that EMG activity normalized 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 normalization (Knudson and Johnston 1993, Burden *et al*. 2003, Gallagher *et al*. 2011). Knudson and Johnston (2011) even argued that the traditional single-angle EMG normalization may be more appropriate for studies of patterns of muscle activation. To obtain normalized EMG

(NEMG) data for this study, a MVC test for each postural muscle at a specific angle was performed (Ericson et al., 1985; Bhattacharya and Ramakrishanah, 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 sec. 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 standardized 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 1st and 4th second of a 30 sec recording period was 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 (standardized 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 standardized resting position, they performed a randomly assigned test condition staring with the fatiguing test (none, half or full). Immediately after completion of the fatiguing task, the subjects stood in a standardized 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 standardized 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):

$$\text{NEMG}(\%\text{MVC})=\frac{\text{Trial EMG signal}-\text{Resting EMG signal}}{\text{MVC EMG signal}-\text{Resting EMG signal}}$$

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, Texas). 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 (%MVC_{50th} and %MVC_{95th}) were calculated from the cumulative APDF curve for each muscle and each trial (Jonsson, 1988). Due to potential spike artifacts, the %MVC_{95th} provides a more reliable EMG measure than the maximum of the EMG activity levels and the %MVC_{50th} provides a more reliable EMG measure as compared to 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 normalize 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 minimized by randomization 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) 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 and B respectively present 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 summarized across the two test conditions.

The %MVC_{50th} of most postural muscles, except tibialii anterior (TA), was smaller than 10% (11.4% for the TA) for all tests conditions. Both %MVC_{50th} and %MVC_{95th} of the TA increased as the inclination angle increased from 0°-26° and exhibited a statistically significant increase for both stationary and research tasks from 14º-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 gastrocnemii medial (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 3–4 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 3 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 1.8–3.3% and 4–7.6%, 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 summarizes 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 Lease 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.

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 to 30.7% MVC) in the $\%MVC_{95th}$ of the TA from 0–26° 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 et al., 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 suggests 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 destabilizing torque in the forward direction for performing the reach task. Approximately a two- to three-fold 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 sec) of performing the reach task during the 30-sec 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 with 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 the present 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 & Sinkjaer, 1992; Doud & 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 hypothesize 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, 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 stabilizing factor for postural balance on a flat (Bhattacharya et al., 1987, 1988; Seliga et al., 1991; Sack et al., 1993; Wang, 1996; Chiou et al., 1998) and inclined surfaces (Simeonov et al., 2009; Kincl et al., 2003). The H-shaped visual cues used in the present study were associated with a stabilizing effect on postural stability on inclined surfaces (Kincl et al., 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 the present study are not as sensitive as the balance stability measures used in the previous studies.

Effect of work experience

The results of the present 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 & Wollacott, 1995). The ability to maintain upright balance depends on the task conditions and the person’s experience (Nashner, 1993). In the present 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 >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 the current study solely replied 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 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 (standardized electrode location, temperature control, and randomization of test sessions) implemented in the study. Despite the non-significant statistical results, between-session variations might not have been controlled completely in the current 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 8 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 below:

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.

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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.

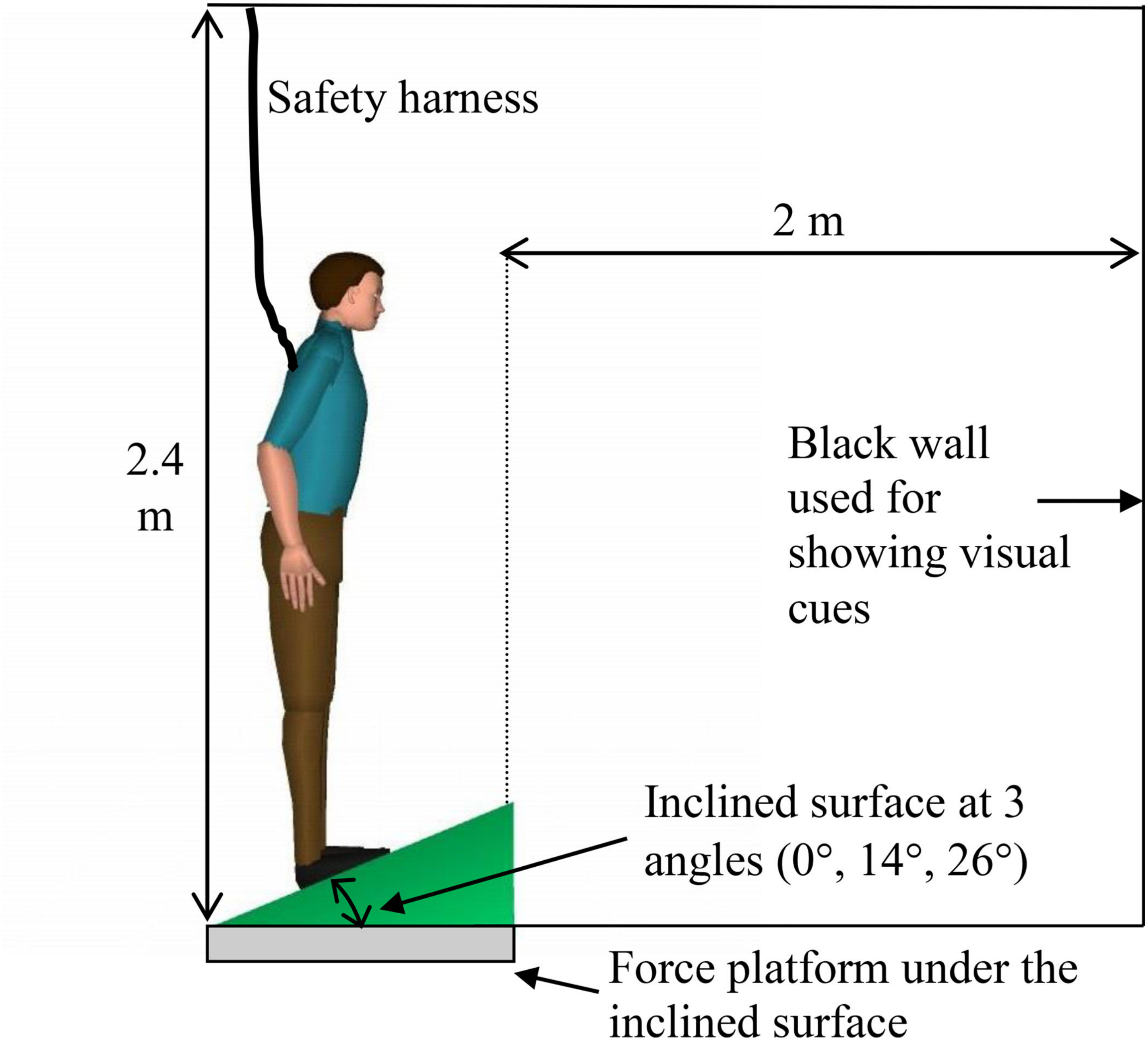

Figure 1.

Schematic layout of the experimental set-up.

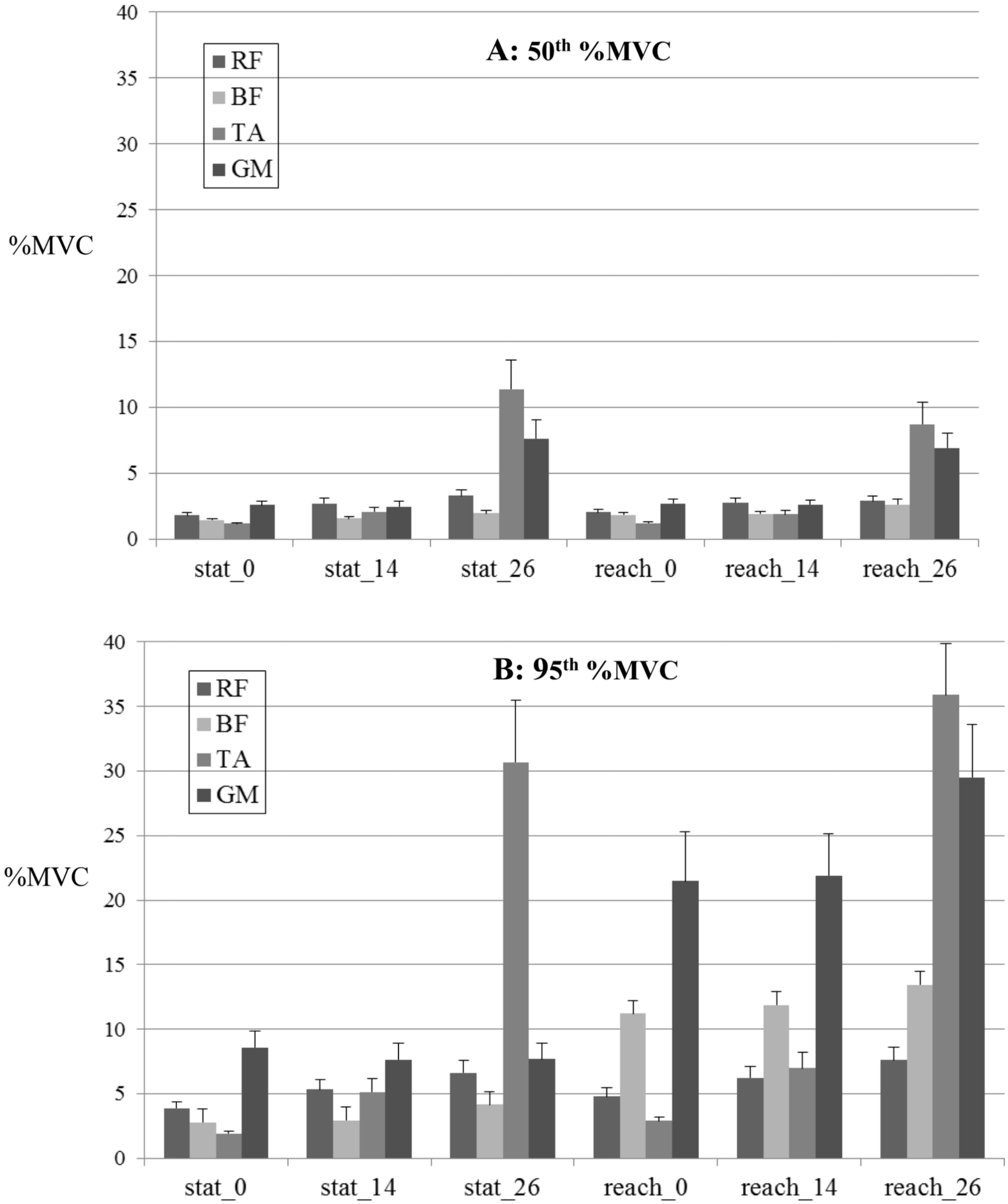

Figure 2.

Geometric means (+ error bars) for the 50th (Figure A) and the 95th (Figure 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, stat_26 represent performing the stationary task on 0°, 14° and 26° inclination, while reach_0, reach_14, reach_26 represent performing the reach task on 0°, 14° and 26° inclinations.

Table 1

Demographics of the subjects, grouped by work experience (experienced: > 3 years; inexperienced: <1 year). Data are mean ± standard deviation.

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

[*] significantly different between two groups ($p<0.05$)

[**] BMI: body mass index.

Table 2

Effects of the experimental conditions on the 50th and 95th percentile NEMG amplitudes of the postural muscles. A: Statistically significant (p<0.05); B: Borderline significant (p=0.05–0.1); C: Not significant (p>0.1).

Experimental Conditions	**NEMG Amplitude Percentile**	**Postural Muscles**							
		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

Table 3

Least Square Means (LSM) for the 50th and 95th percentile EMG amplitudes of the left and right rectus femoris (RF) 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

[*] Statistically significant (p<0.05)

[**] Borderline statistically significant (p<0.09)