
Volume 24, Issue 1, February 2014
ISSN 1050-6411
ELSEVIER
JOURNAL OF
ELECTROMYOGRAPHY
AND
KINESIOLOGY
OFFICIAL JOURNAL OF
THE INTERNATIONAL SOCIETY OF
ELECTROPHYSIOLOGY AND KINESIOLOGY
AND THE JAPANESE SOCIETY OF
ELECTROPHYSIOLOGICAL KINESIOLOGY

Journal of Electromyography and Kinesiology 24 (2014) 159–164

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Muscular responses to handle perturbation with different glove condition

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A R T I C L E I N F O

Article history:
Received 27 April 2013
Received in revised form 24 September 2013
Accepted 3 October 2013

Keywords:
Muscle effort
Muscle reaction time
Tactile sensation
Finger pressure
Cutaneous reflex

A B S T R A C T

Effect of wearing gloves on timely muscle reaction to stabilize handle perturbation was investigated. Thirteen adults gripped a horizontal overhead handle to which an upward force was applied at a random time. Muscle reaction time, integrated EMGs for eight muscles, and handle displacement were compared among three glove conditions affecting the coefficient of friction (COF = 0.32, 0.50, and 0.74 for the polyester glove, bare hand, and latex glove, respectively). Lower COF increased the integrated EMGs and handle displacement until stabilization of the perturbed handle. The low-friction glove resulted in 16% ($p = .01$) greater muscular effort and 20% ($p = .002$) greater handle displacement, compared to the high-friction glove. Muscle reaction time was not influenced by glove condition. Cutaneous sensation and reflex eliciting forearm muscle activity appear to play an important role in detecting and responding to the perturbation initially, while the forearm and latissimus dorsi muscles primarily contribute to stabilizing the perturbed handle compared to other shoulder and upper arm muscles. Therefore, low-friction gloves, cutaneous sensory dysfunction, and weakened forearm and latissimus dorsi muscles may jeopardize persons' ability to stabilize a grip of a handle after perturbation.

1. Introduction

Gloves are frequently used in workplaces to protect workers' hands (Kinoshita, 1999). The way gloves affect a person's biomechanical response to perturbation, however, has not been thoroughly studied despite myriads of practical applications. One such application is falls from ladders and scaffolds, which make up the biggest cause of fatal falls to lower levels (BLS, 2009). When a person misses a step, the primary method of preventing a fall is to rapidly tighten the grip of a ladder or scaffold to support the body or to slow down the body's fall until safe footing is established. Upon a missed step, the sudden loading at the hand and handle is one of the cues that can be used to detect the initiation of a fall and to quickly respond. Gloves may influence the detection of the sudden loading at the hand and response to tighten the grip for the following reasons.

First, gloves may obstruct the cutaneous sensation of the hand, thereby slowing down one's detection of, and response to perturbation. Wearing gloves reduced cutaneous sensitivity of the hand, likely by interfering with mechanoreceptors' ability to obtain appropriate information (Shih et al., 2001). Consequently, gloves deteriorated the dexterity of the hand and slowed down hand movements (Bradley, 1969; Plummer et al., 1985; Bensal, 1993; Nelson and Mital, 1995). Delayed detection of, and response to perturbation could be life-threatening when a person has to recover from an initiated fall from a scaffold/ladder.

Second, gloves may increase the muscular effort to stabilize a grip of a handle after perturbation. Specifically, gloves with low friction led to excessive grip effort (Frederick and Armstrong 1995; Kinoshita 1999) and reduced hand strength (Enders and Seo 2011; Seo et al. 2011; Hur et al. 2012), causing early onset of muscular fatigue of the hand (Fleming et al. 1997). These reports suggests that to stabilize a handle against a given load, greater muscle activity may be demanded if low-friction gloves are worn, compared with high-friction gloves.

Third, low-friction gloves may increase handle displacement until its stabilization after perturbation. A simulation study by Barnett and Poczynck (2000) projected that, compared with high-friction gloves, low-friction gloves would increase the falling distance of a person holding onto side rails of a fixed ladder upon a misstep.

The objective of this study was to determine the effect of gloves on a person's timely upper limb muscular response to stabilize a grasped handle after a perpendicular load perturbation to the handle. The rationale of this study was to provide some insights on a

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http://dx.doi.org/10.1016/j.jelekin.2013.10.004

person's biomechanical response to a misstep from a scaffold/fixed vertical ladder. It is acknowledged that the hand may not always be in contact with horizontal scaffolds/rungs at the time of missteps. In addition, the sudden perturbation at the handle is just one of many cues that people can use to detect the initiation of a fall from a scaffold/ladder, including visual, vestibular, and proprioceptive cues, as well as the tactile cues at the foot. However, as an initial step toward understanding the critical ability to rapidly activate the upper limbs and stabilize a grip to prevent a fall and how this biomechanical response is compromised with gloves, the present study focused on a reduced scope of the effect of gloves on the upper limb's biomechanical response to perturbation of a grasped handle.

Based on the previous knowledge on how gloves affect grip manipulations, it was hypothesized that wearing gloves would increase the reaction time to handle perturbation and a low-friction glove would lead to increased muscular efforts to stabilize the perturbed handle, as well as increased handle displacement until stabilization. To test this hypothesis, an experiment was conducted to examine the effect of a high- and low-friction glove as well as the bare hand on the muscle reaction time, the muscular effort over time, and the handle displacement upon handle perturbation. The time course of muscular responses was additionally examined to elucidate the details of the event after the perturbation.

2. Methods

2.1. Participants

Thirteen right-handed healthy young adults participated in the study (9 males and 4 females, mean ± standard deviation of age, 25 ± 5 years; height, 171 ± 13 cm; weight, 69 ± 15 kg; body mass index (BMI), 24 ± 4 kg/m^2). Healthy young adults with ages between 20 and 35 years were included. Persons who had any of the following conditions were excluded from the experiment: (1) cognitive dysfunction that precludes comprehension of experimental tasks, (2) inability to understand English and (3) history or clinical signs of orthopedic or neurologic disorders. The subjects were found not to have engaged in physically strenuous activities prior to the experiment. The subjects' nondominant hand was tested because people typically hold onto a rung of a vertical fixed ladder, scaffold, or hand rail with their nondominant hand even when they use their dominant hand for another task (e.g., reaching for something, painting) (Smith et al. 2006). The protocol was approved by the Institutional Review Board at the University of Wisconsin-Milwaukee. All subjects gave written informed consent before engaging in the research experiments.

2.2. Procedure

The subjects held a horizontal handle with the nondominant hand, using minimal effort while seated in the posture shown in Fig. 1. Mimicking a rung holding posture, the initial upper limb posture was approximately 160° shoulder flexion, 10° elbow flexion and 0° wrist flexion. Subjects were asked to stabilize the handle when the handle was perturbed at a random time. The handle perturbation was administered by dropping a weight that was connected to the handle via cables (Fig. 1). The weight was equivalent to 20% of the person's hand strength to resist the handle (Hur et al. 2012) to not jerk subjects' arms but to have strong enough perturbation to evoke muscular responses. Subjects were instructed to look to the front during the experiment so that they could not see the perturbation being applied in the back or above their head (Fig. 1).

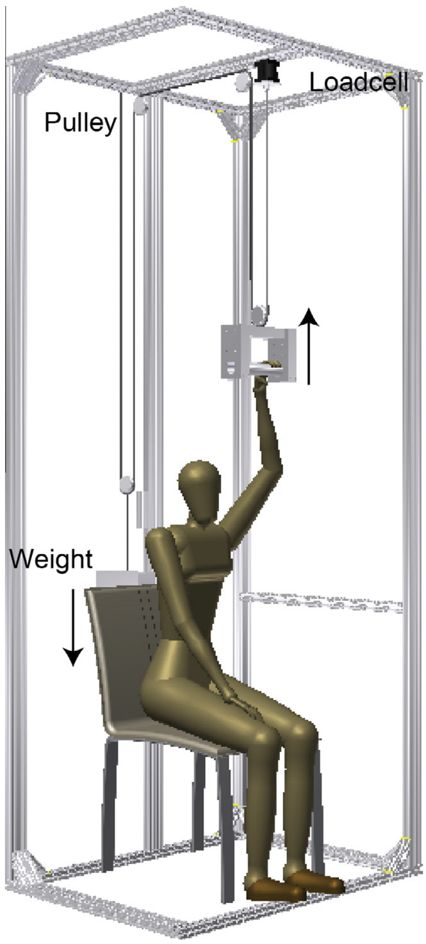

Fig. 1. Experimental setup. The subject was instructed to stabilize the handle when the handle was perturbed at a random time via a drop of a weight.

To describe the subjects' responses to the perturbation, the time course of the force registered on the handle, the muscle activities, and the handle displacement were recorded. The handle force was computed as twice the force recorded on a load cell (SM-1000, Interface Inc. Scottsdale, AZ) measuring tension of the cable holding a movable pulley to which the handle was attached (Fig. 1). The handle force data were sampled at 1 kHz.

For muscle activities, a surface electromyogram (EMG) (Bortec Biomedical Ltd., Calgary, AB, Canada) was recorded for the following 8 muscles: flexor digitorum superficialis (FDS), flexor carpi ulnaris (FCU), extensor digitorum communis (EDC), biceps, triceps, deltoid, pectoralis major, and latissimus dorsi. These 8 muscles were chosen for their important roles in moving and stabilizing the upper limb (Richardson 2011). Bipolar Ag/AgCl surface electrodes (1 cm diameter with a 2.5 cm interelectrode distance) were placed on the skin overlying the muscle belly. The muscle was located by using the anatomical landmarks following the literature (Basmajian 1989) and confirmed through palpation and visual observation of EMG signals from an oscilloscope while the subjects performed a muscle-specific movement (Smith et al. 1996). The skin was prepared by shaving the hair, if needed, and cleaning with alcohol swabs, to reduce the impedance before the electrodes were placed. All EMG signals were sampled at 1 kHz. The maximum voluntary contraction (MVC) of each muscle was recorded. For analysis, the root mean square (RMS) EMG with 10 ms moving windows normalized by the MVC of each muscle was used. For handle displacement, the handle position was recorded by using the 3D Investigator™ Motion Capture System (Northern Digital Inc., Waterloo, ON, Canada) at 100 Hz.

The handle perturbation procedure was repeated three times for each glove condition to compute the mean. The following three glove conditions (Fig. 2) that are frequently encountered at workplaces were used (OSHA 2003; Fix8 2011): (1) the polyester glove (HD55080/FACP, West Chester, Inc., Monroe, OH), (2) the bare hand, and (3) the latex glove (HD30503/L3P, West Chester, Inc., Monroe, OH). These three glove conditions have different coefficients of friction (COFs) against the aluminum handle of 0.32, 0.50, and 0.74 (SD = 0.06, 0.08, and 0.12), respectively (Hur et al. 2012). The order of testing each glove condition was randomized across the subjects. A minimum of two minute breaks was given between consecutive tests to prevent muscle fatigue.

2.3. Data analysis

To test the hypothesis, the effect of the glove conditions on the muscle reaction time, the muscular effort over time, and the handle displacement upon handle perturbation were investigated. The onset of handle perturbation was determined as when the rate change of the handle force exceeded 50 N/s for more than 20 ms (Fig. 3). The muscle reaction time was determined as the earliest muscle reaction time among the 8 muscles. The reaction time for a muscle was defined as the time interval between the handle perturbation and when the muscle's RMS EMG exceeded 3 standard deviations above the baseline muscle activity (Seo et al. 2009). The muscular effort was determined by integrated EMG (% MVC-s) during the time period between when the handle was perturbed and when the handle stopped moving upward (Fig. 3). The handle displacement was the distance that the handle traveled during the same period (Fig. 3). In addition, the time at which the handle started moving up was determined to describe the event after the perturbation in detail. The onset of the handle movement was determined as when the rate change of the handle displacement was greater than 100 mm/s for more than 50 ms (Fig. 3). Handle stabilization time was determined as when the rate change of the handle displacement was smaller than 50 mm/s for more than 100 ms (Fig. 3).

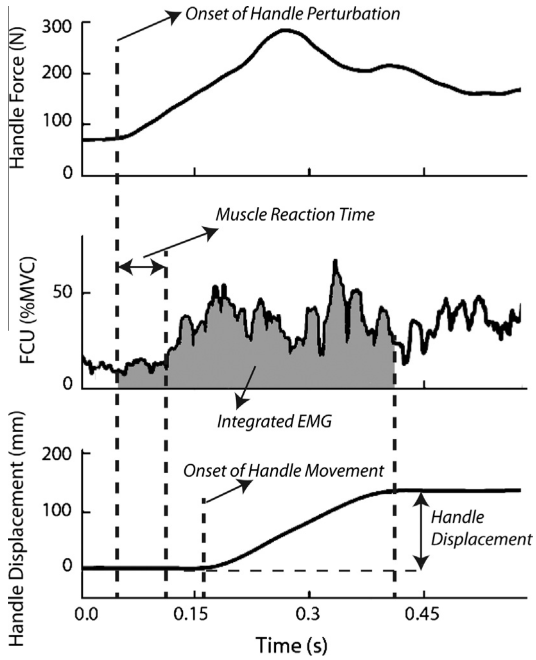

Fig. 3. Time course of responses to handle perturbation. Handle force, RMS EMG of the muscle that reacted the first (FCU muscle in this trial), and handle displacement are shown on the top, middle, and bottom, respectively.

Fig. 2. The polyester glove (a) and latex glove (b) are commonly used at workplaces to protect workers' hand. These gloves can change the coefficient of friction at the hand-handle interface.

2.4. Statistical analysis

Three repeated measures analyses of variance (ANOVA) were performed for each of the three main responses using SPSS Statistics v17.0 (SPSS Inc., Chicago, IL). The first ANOVA determined if the earliest muscle reaction time was significantly affected by the glove condition. The second ANOVA determined if the integrated EMG was significantly affected by the glove condition and the muscle. The third ANOVA determined if the handle displacement significantly varied with the glove condition. The level of significance was $p < 0.05$. Post-hoc tests used Fisher's least significant difference. As secondary analysis, another ANOVA determined if reaction time significantly differed by individual muscles. Values are presented as mean ± standard error throughout the paper unless otherwise specified.

3. Results

The overall time course of the muscle activity and the handle displacement after the handle perturbation was as follows (pooled for all glove conditions and subjects). The earliest muscle activation occurred 44 ± 2 ms after the handle perturbation. The handle started moving upward in 60 ± 6 ms after the handle perturbation. The handle was stabilized 304 ± 25 ms after the perturbation. A sample time course is shown in Fig. 3.

The earliest muscle reaction time to the handle perturbation was not significantly affected by the glove condition ($p > 0.05$), although the trend of the shortest muscle reaction time for the bare hand was seen in Fig. 4a. Among the 8 muscles, the forearm muscles reacted significantly earlier to the handle perturbation than the other muscles (Fig. 4b).

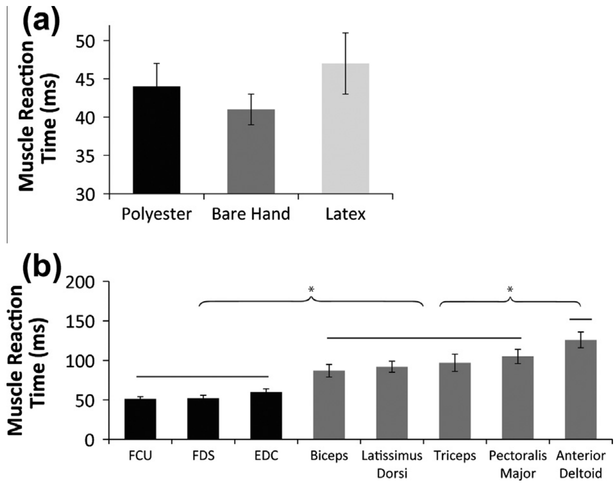

Fig. 4. (a) The earliest muscle reaction time for the three glove conditions (earliest among all muscles). (b) The reaction time for individual muscles (pooled for the glove conditions). The forearm muscles (black bars) were activated earlier than the other muscles (grey bars). Error bars represent ± one standard error. A horizontal line indicates a group without statistically significant differences. A star distinguishes two groups with statistically significant differences based on the post hoc results.

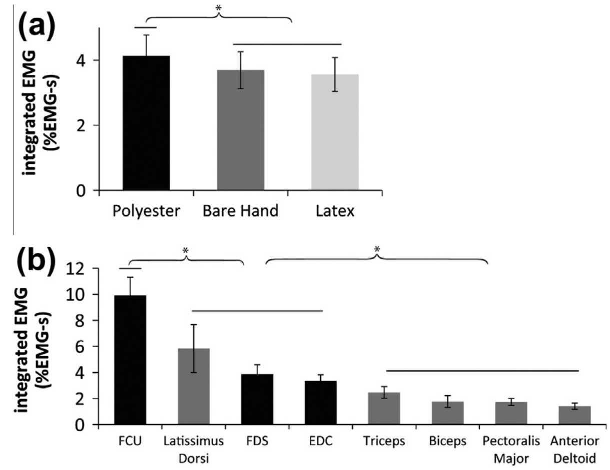

Fig. 5. (a) Integrated EMG (pooled for all muscles) decreased with increasing COF at the grip interface. The polyester glove with the lowest COF resulted in the highest integrated EMG to stabilize the perturbed handle compared to bare hand ($p = 0.03$) and latex glove ($p = 0.01$) conditions. (b) Integrated EMG (pooled for the glove conditions) was the highest for the FCU muscle, followed by the other forearm muscles (black) and latissimus dorsi, and by the upper arm and shoulder muscles. Error bars represent ± one standard error. A star indicates groups with statistically significant differences.

The mean integrated EMG increased with a decreasing COF at the grip interface (Fig. 5a). The mean integrated EMG for the polyester glove was 16% greater than for the latex glove. The ANOVA showed the significant main effect of the glove condition ($p = 0.02$). Post hoc tests revealed that the integrated EMG for the polyester glove was significantly greater than that for the bare hand ($p = 0.03$) and the latex glove ($p = 0.01$). In addition, the magnitude of the integrated EMG significantly varied by the muscle ($p < 0.001$). Post hoc tests showed that the integrated EMG was the highest for the FCU, followed by the latissimus dorsi, FDS, and EDC, then by the upper arm and shoulder muscles (Fig. 5b).

Displacement of the perturbed handle also increased as the COF at the grip interface decreased (Fig. 6). The handle displacement was 20% greater for the low-friction polyester glove compared with

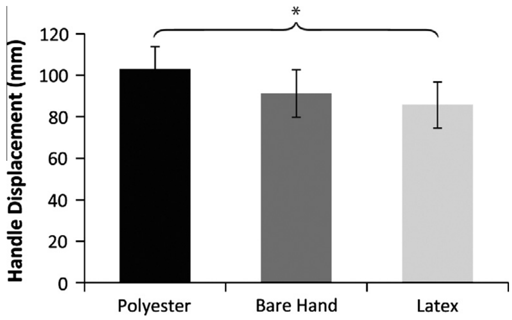

Fig. 6. Handle displacement decreased with increasing COF at the grip interface. The polyester glove with the lowest COF condition resulted in the greatest handle displacement until stabilization of the perturbed handle compared to latex glove condition ($p = 0.002$). Error bars represent ± one standard error. A star indicates a statistically significant difference.

the high-friction latex glove. The ANOVA showed the significant main effect of the glove condition ($p = 0.01$). Post-hoc tests revealed that the handle displacement for the polyester glove was significantly greater than that for the latex glove ($p = 0.002$).

4. Discussion

4.1. Effects of gloves in stabilizing a perturbed handle

The results suggest that a decreased COF at the hand-handle interface with slippery gloves may be detrimental for stabilizing the grip of a handle after perturbation, due to the increased muscle effort required and the greater perturbed distance before stabilization. However, the muscle reaction time was not significantly affected by the two gloves investigated in this study. The detailed discussions are as follows.

The earliest muscle reaction time was not affected by wearing gloves although the trend of the shorter muscle reaction time for the bare hand was seen (Fig. 4a). It is possible that since the gloved hand was already grasping the handle, the glove was preloaded by the weight of the subject's arm and fully deformed at the time of perturbation. Thus, these gloves may not have significantly interfered with the transmission of the perpendicular perturbation load to the hand. If the glove was bulky, the transfer of the perturbation force from the handle to the hand could have been dampened, delaying the detection of the handle perturbation.

The integrated EMG increased with a decreasing COF at the hand-handle interface (Fig. 5a). The low-friction polyester glove resulted in 12% and 16% greater integrated EMG to stabilize the perturbed handle, compared with the bare hand and the high-friction latex glove, respectively. Our results align with the previous finding where a decreased COF increased the muscular effort in twisting handles (Seo et al. 2008). The greater muscular effort needed for the low-friction polyester glove may be related to the reduced ability of the hand to apply force to a handle when the low-friction polyester gloves are worn, compared with the bare hand or the latex glove (Hur et al. 2012).

The handle displacement before stabilization also increased with a decreasing COF at the hand-handle interface (Fig. 6). The low-friction polyester glove resulted in 13% and 20% greater handle displacement, compared with the bare hand and the high-friction latex glove, respectively. This result is in agreement with the simulation-based study that predicted that wearing gloves with low COFs increases the falling distance from a ladder (Barnett and Poczynck 2000). In summary, gloves resulting in low friction between the hand and the handle should be avoided because of the greater muscular effort needed to stabilize a handle as well as the greater falling distance expected after perturbation.

4.2. Role of somatosensation detecting pressure at the hand

The somatosensation of the hand detecting pressure applied to the hand skin and tissue, not the spindles of the upper limb muscles, appears to have detected the perturbation and triggered the earliest muscle activation in this study. Specifically, the handle started moving upward 60 ± 6 ms after the handle force increased (pooled for all glove conditions) (Fig. 3), indicating that changes in the joint angles (related to proprioception for detecting changes in the muscle length) occurred 60 ± 6 ms after the mechanoreceptors in the hand could register the force increase between the hand and the handle. In addition, before any changes in the joint angles, the earliest muscle was already activated 44 ± 2 ms after the mechanoreceptors detecting the force increase at the hand against the handle.

The earliest muscle reaction in this study appears to be a reflex response. The earliest muscle reaction time of 44 ± 2 ms appears to be too short for a voluntary response, given that the simple reaction time for healthy young adults is 135–220 ms for sound or visual stimuli (Brebner and Welford 1980; Welford 1980; Jaeger et al. 1982; Mojica et al. 1988; Anstey et al. 2005). The mechanism for the earliest forearm muscle reaction is potentially a spinal reflex triggered by the somatosensation detecting the increased pressure on the hand. Hagert et al. (2009) reported that the forearm muscles were activated within 40 ms after stimulation of a wrist ligament. The latency due to this wrist proprioceptive reflex (Hagert et al. 2009) as well as the latencies reported in other similar studies including cutaneous reflexes (33–45 ms) (Garnett and Stephens 1980; Jenner and Stephens 1982; Corden et al. 2000; Zehr et al. 2001) are similar to the latency of 44 ms in our study. This similar latency suggests that in the present study, the forearm muscles may have been activated through cutaneous and/or proprioceptive reflex mechanisms in response to the detection of the hand pressure increase after the rung perturbation. It is unlikely that the earliest forearm muscle activation was mediated by a stretch reflex, since stretch reflex latencies for the upper extremity muscles are shorter than 40 ms (Corden et al. 2000) and no movement that could trigger a stretch reflex was detected before the earliest muscle reaction, as discussed in the previous paragraph. On the other hand, the reaction of the upper arm and shoulder muscles may have been mediated by different mechanisms. The upper arm and shoulder muscles were activated 90–125 ms (Fig. 4b) after the handle force increase, which may be still too early to be voluntary movements (Brebner and Welford 1980; Welford 1980; Jaeger et al. 1982; Mojica et al. 1988; Anstey et al. 2005), and too late to be polysynaptic propagation of the reflex for the same hand pressure stimulus that triggered the forearm muscle activation (Zehr et al. 2001). Given that the upper arm and shoulder muscles were activated approximately 30–65 ms after the handle started moving (Figs. 3 and 4b), the activation of the upper arm and shoulder muscles could possibly be due to stretch reflexes induced by sudden changes of muscle lengths at the elbow and shoulder joints in addition to reflexes involving mechanoreceptors.

4.3. Role of forearm and latissimus dorsi muscles

The forearm muscles and the latissimus dorsi muscle were activated with greater efforts than other muscles to stabilize the perturbed handle, as evidenced by greater integrated EMG (Fig. 5b). In addition, the muscle reaction time was earlier for the forearm muscles than for other muscles (Fig. 4b). These findings suggest that grasping with the forearm muscles and pulling the handle down via depression of the scapula with the latissimus dorsi (Richardson 2011) play important roles in responding to and stabilizing handle perturbation.

4.4. Functional implications

The present study demonstrates that one's ability to stabilize a grip of a handle upon perturbation suffers from the use of slippery gloves such as the polyester glove. The present study also suggests that impaired somatosensation detecting pressure at the hand and weak forearm and latissimus dorsi muscles could deteriorate one's ability to respond to and stabilize handle perturbation. If applied to the scenario of a misstep on a scaffold/ladder perturbing the grip of the handle/rung, this study suggests that the risk of unsuccessful recovery from the misstep, leading to fall and injury, may increase with slippery gloves or other conditions reducing COF, such as oily contamination. The risk of injury may also increase with sensory dysfunction and weakened forearm and latissimus dorsi muscles. High COF conditions at the hand-handle interface and strengthening of the forearm and latissimus dorsi muscles may help recovery. However, these predictions should be verified in studies simulating a whole-body fall from a misstep, since the present study had a reduced scope of investigation for only the upper limb response to handle perturbation.

4.5. Limitation and future study

While the present study provides preliminary evidence for how gloves affect a person's ability to stabilize a grip of a handle in response to perturbation, in order for these findings to be applicable to the scenario of falling from scaffolds/ladders, further studies involving falls from a real scaffold/ladder are needed. Such studies would incorporate all senses, including the vestibular sensation, vision, and somatosensation of the lower limb. Such studies may dichotomize fallers and nonfallers depending on factors such as a person's reaction time, muscular strength, and somatosensory threshold. The upper extremity posture during the experiment was different from the posture when EMG electrodes were places. This posture difference may have affected EMG recordings. However, it may not change the conclusion of this experiment due to repeated measures within-subject research design. During the experiment, there was a small clicking sound associated with the application of the perturbation. Although this sound was present consistently for all glove conditions, the study found that muscle effort and handle displacement were still significantly affected by the glove condition. However, future studies may consider using devices such as noise-canceling headphones to eliminate any sound effects. The muscle reaction time reported in this study was obtained for young healthy adults only. It is to be noted that muscle reaction time may be different depending on age and BMI (Rein et al. 2010).

5. Conclusion

This study demonstrated that the low-friction polyester glove increased the muscular effort required to stabilize a grip of a handle after perturbation as well as increased the perturbed distance before stabilization, while not slowing the muscular reaction to perturbation. The present study suggests that spinal reflex eliciting forearm muscle activity in response to the change in pressure at the hand appears to depend on somatosensation. The spinal reflex with a short latency time may play an important role in the initial response to a perturbation. The latissimus dorsi muscles as well as the forearm muscles show a large activity level compared with other shoulder and upper arm muscles and may play a major role in the later stabilization of the perturbed handle. The results of this study have implications for reducing injuries due to falls from elevation by implementing high friction conditions between the hand and the handle and strengthening the forearm and latissimus dorsi muscles.

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Conflict of Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

This work was supported by the NIOSH University of Illinois at Chicago Education and Research Center T42 OH008672. Authors also thank Dr. Marjorie P. Piechowski for proofreading the manuscript.

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