Experimental assessment of effectiveness of arm-supporting exoskeleton for overhead work

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Abstract

It is well known that overhead work is associated with musculoskeletal disorders in the upper extremities. Arm-supporting exoskeletons (ArmExos) help to reduce mechanical load to the shoulder joint and subsequently risk of injury in the area. The ArmExos are adopted rapidly by industries such as car and airplane manufacturers, although there lack studies examining the effectiveness of the ArmExos in these industry settings as the associated overhead tasks often involve use of power hand tools. To simulate overhead tasks with use of power hand tools, an electromagnetic shaker was hung from the ceiling and produced a random vibration spectrum modified from the ISO 10819. In this posture the ArmExos exerted the highest torque to the upper arm when it was flexed 90 degrees. As comparison, the shaker was also placed in front of the body, in which the ArmExos produced minimum torque to the upper arm when it was hanging down along the body. Vibration transmissibility along the arm and the spine was monitored using accelerometers. Activity of the shoulder muscles was obtained using surface electromyography. The grip force was assessed in the shaker handle while the push force was assessed using a force plate placed under subject's feet. Live feedback was shown on a computer monitor for the subjects to maintain an average grip force at 30 N and an average push force at 50 N. The data demonstrated that wearing ArmExos didn't alter vibration transmissibility along the body. Wearing ArmExos led to lower shoulder muscle activities. The agonist muscle activities in the overhead posture were higher when compared to the front-of-body posture. Antagonist muscle activities tended to increase with vibration turned on. The existence of vibration significantly increased the peak grip force and push force, indicating a higher mechanical load to the shoulder. These findings suggest that the impact of ArmExo use in overhead tasks involving power tools is complex. Shoulder joint load analysis using advanced musculoskeletal models is recommended to understand the effectiveness of ArmExos in such industry settings.

Keywords: exoskeleton, work posture, vibration, muscle activity.

Introduction

Musculoskeletal disorders (MSDs) are painful disorders of muscles, tendons, joints, and nerves commonly occurring in the neck, shoulder, arm, and back regions. According to the 2019 US Bureau of Labor Statistics survey of nonfatal occupational injuries and illness, a total of 272,780 MSD cases were reported in private industry in 2018. Among them, 86,410 cases were injuries in the upper extremities, including sprains, rotator cuff tears, arthritis, tendinitis, and bursitis. It is noteworthy that one half of the upper extremity MSD cases occurred at the shoulder joint, suggesting that this joint is the weakest part in the upper extremities. The upper extremity MSDs are more disabling as indicated by a median of 20 days away from work compared to a median of 12 days away from work for all MSDs. One particular physical exposure contributing to upper extremity MSDs is overhead work in which workers need to raise one or both arms above their shoulders for a substantial time of their work schedule. This in part explains a high prevalence of upper extremity MSDs in industrial sectors such as that often involve overhead tasks. Overhead work is particularly detrimental to the shoulder joint due to several biomechanical disadvantages, including exertion away from the optimal working range of shoulder muscles, a faster fatigue rate, and reduced ability to maintain joint stability. Safety measures such as decreasing the load, modifying the arm working posture, raising body position, and limiting exposure time have been recommended to reduce the risk associated with overhead work.

In recent decades, occupational exoskeletons have received great attention for their potential to improve efficiency, increase productivity, and reduce injuries (Kim et al., 2018). According to a recent systematic literature review of the effectiveness of workplace interventions (Van Eerd et al., 2016), arm support is the only intervention shown to be moderately effective in reducing the upper extremity MSDs, while most other interventions, such as workstation adjustment, work redesign to minimize shoulder load, ergonomic training, and attendance at an occupational health and safety workshop, appear to be ineffective. The early adopters of arm-supporting exoskeletons (ArmExos) include manufacturing industries. It is noteworthy that in these industries, hand-operated power tools are often used when wearing Exos (Kamping-Carder, 2019). For example, Boeing has about 100 passive ArmExos across five site locations in the US, with 100% of the users working with vibratory tools. Toyota Motor North America has acquired Exos for 500 workers across six vehicle plants in North America, with most using vibratory tools. Ottobock, a major exoskeleton developer and manufacturer, reported that it has placed their products in over 1,000 plants worldwide, where about 80% of the plants are for manufacturing with 100% of those environments requiring the use of hand tools.

Because the ArmExos can decrease the physical load experienced by the users, particularly during overhead work, the rate of implementation into the workplace continues to exceed the research results needed to demonstrate short-term and long-term effectiveness (De Looze et al., 2016). Additionally, there is a lack of guidelines available for developers to design effective Exos or for users to select the proper Exos for specific work environment (Lowe et al., 2019). Therefore, the purpose of this research was to collect preliminary data that can be used to investigate the effectiveness of ArmExo in dealing with the combined effects of overhead posture and power hand tools. The preliminary study outcomes involved vibration transmissibility (VT) along the arm and the upper body, electromyography (EMG) activities from muscles surrounding the shoulder joint, and coupling forces (i.e., grip force and push force) between the users and the tool handle. These data will be fed into DHM in future studies to examine the comprehensive effects of ArmExo in overhead work with use of power hand tools.

Methods

Subjects

For this preliminary study, two right-handed, healthy male participants were recruited with age between 18 and 60, hand size between 7 and 10 (ISO 10819, 2013), and no history of major musculoskeletal injury or surgery. The participants underwent informed consent process, and their signatures were obtained. The study was carried out at the main campus of Northern Illinois University, DeKalb, IL with the IRB approval number HS20-0219.

Experimental Procedures

A full-factorial, nested design using within-subject comparisons was employed to investigate 1) VT along the arm and the spine, 2) shoulder muscle EMG, and 3) coupling forces when the subjects were exposed to simulated tool vibrations. The three main factors in this nested design are: posture condition as level 1 (overhead – OH and front-of-body – FOB), Exo condition as level 2 (vest-type Exo, strap-type Exo, and not wearing Exo); and vibration condition as level 3 (vibration turned on and turned off), or a total of 12 testing conditions. Each condition was repeated 3 times or a total of 36 recordings for each subject. In the present study, muscle activities were collected using a surface EMG system. A maximum voluntary contraction (MVC) procedure was necessary to normalize the EMG data for between-subject comparisons and within-subject comparisons of multiple study visits. The MVC test was done before the main tests.

Posture conditions

An overhead posture and a front-of-body posture were examined in the present study. For the overhead posture, both the elbow and shoulder joints were flexed 90° in the sagittal plane (Figure 1.a). The front-of-body posture was defined in the ISO 10819 (2013), in which the forearm was flexed 90° and the upper arm hangs down in a natural position (Figure 1.b). A scissor lift (Presto Lifts Inc, Norton, MA) was used to adjust subject standing height such that the arm posture is standardized across all subjects and all testing conditions.

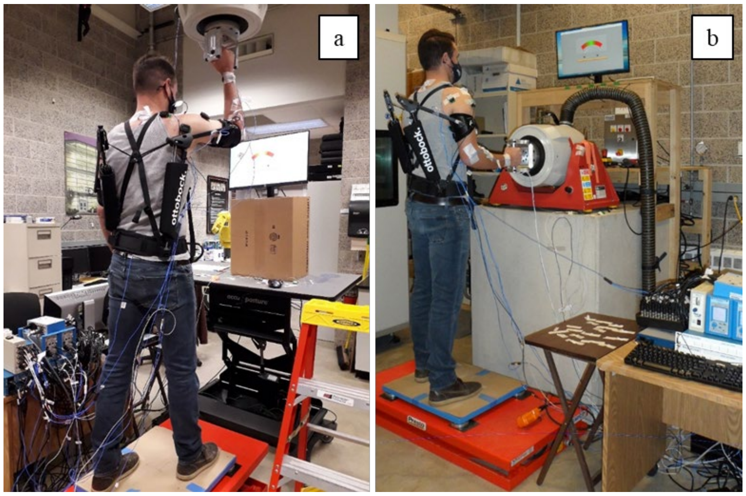

Figure 1. Illustration of the overhead posture (a) and the front-of-body posture (b).

<u>Exoskeleton conditions</u>

Two commercially available Arm Exos were used in the present study, including 1) a vest-type Exo – EksoVest, Model V-1.0-0574, Ekso Bionics, Richmond, CA (Figure 2.b) and a strap-type Exo – Paexo Shoulder, Model 6ES100=2, Ottobock, Duderstadt, Germany (Figure 2. c). A condition of not wearing ArmExo was also tested to serve as control (Figure 2.a).

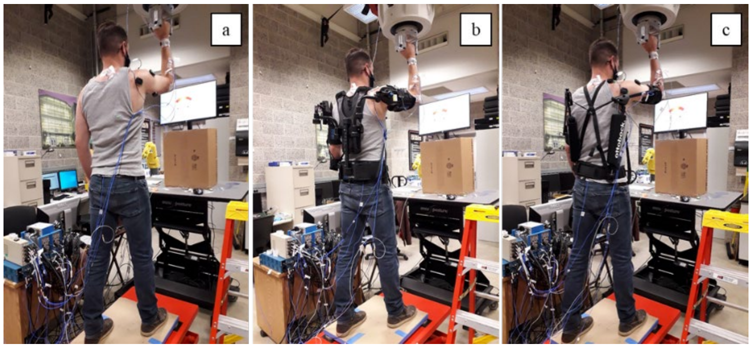

Figure 2. Illustration of not wearing exoskeleton (a), wearing a vest-type exoskeleton (b), and wearing a strap-type exoskeleton (c).

Vibration conditions

The power tool vibration was simulated using an electromagnetic shaker (LDS V651 shaker, Brüel & Kjær, Nærum, Denmark). A vibration control system (VR8500, Vibration Research, Jenison, MI) was used to drive the shaker. The vibration spectrum was adapted from the random vibration spectrum defined in the ISO 10819 (2013) with the lower limit extended from 25 Hz to 2 Hz while the upper end remaining at 1600 Hz. Data analysis demonstrated that the shaker could drive random vibration with a lower limit of approximately 7 Hz, which was used in data analysis.

Test sequence

The nested design was chosen to minimize fatigue and streamline the testing procedures. Because the time needed for the overhead shaker setup takes about 4 to 5 hours and 1 to 2 hours for the front-of-body setup, two study visits were required to accommodate the two posture conditions. Additionally, the two vibration conditions were examined with the no vibration condition tested first immediately followed by the vibration turned on. There was a one-minute separation between the two vibration conditions as it takes the shaker approximately 1 minute to achieve the designated waveform and amplitude. The subjects were allowed to have a 3-minute break before the next testing trial to prevent muscle fatigue. The time to change ArmExo was about 5 minutes, thus no extra rest was needed between the exoskeleton conditions. The Exo conditions were permutated using a Latin Squares – Williams design.

Outcome measures

Vibration transmissibility

To understand VT along the arm and the spine, vibration was assessed using triaxial accelerometer placed at the wrist (between radial and ulnar styloid process), elbow (lateral epicondyle), shoulder (acromion), and upper back (C7), middle back (T10), and lower back (L3). One additional triaxial accelerometer was placed at the right arm-link of the ArmExos. The VT was calculated between the acceleration at different body locations and the acceleration at the shaker handle. Since the vibration response of the human body is frequency dependent, VT was treated in the frequency domain using power spectral density (PSD). The overall VT was calculated as the area under the curve of PSD between 7.3 Hz and 500 Hz. Note that the PSD value is the root-mean-square (RMS) amplitude squared. The VT calculated this way is the squared value of VT calculated using RMS amplitude.

Electromyography

A 16-channel wireless surface EMG system (Trigno, Delsys Inc., Natick, MA) was used to obtain activities of nine muscle surrounding the shoulder. These muscles included anterior, medial, and posterior deltoids, upper trapezius, latissimus dorsi, pectoralis major; serratus anterior, biceps brachii, and triceps brachii. Prior to surface EMG sensor attachment, the skin over the target muscles was shaved if necessary and cleaned using alcohol pads twice to attenuate impedance. The EMG signals were output as analog signals for recording.

Couple forces

To standardize testing within- and between-subjects, the coupling forces (i.e., grip force and push force) were tightly controlled based on the coupling forces specified in the ISO 10819 (2013). The grip force assessment was conducted with subjects held onto the shaker handle instrumented with two uniaxial force transducers (Kistler model 9212, Kistler amplifier type 5018, Kistler Instrument Corp., Novi, MI). The push force assessment was conducted using a Kistler force plate (model 9260AA, amplifier type 5233A, Kistler Instrument Corp., Novi, MI) was placed under the subject's feet. A computer monitor was placed in front of the subjects to provide live feedback to control the grip force and push force levels at 30 N ±5 N and 50 N ±8 N, respectively (ISO 10819, 2013)

Acceleration, EMG, and force signals were recorded using a custom-written LabVIEW program (Version 17, National Instrument, Austin, TX) and with two 32-channel analog-to-digital converters (NI USB-6363 and NI–9205, National Instrument, Austin, TX). The sampling frequency was set at 5000 Hz. The sampling duration was 12 seconds for each testing condition. A custom-written MATLAB program was used to calculate all outcome values. The average of 3 trials was used to conduct descriptive analysis.

Results

Figure 3 shows the VT along the body as compared to the shaker handle when split according to exoskeleton conditions. The overall trend of the VT was not affected. The same observation was made when splitting data according to the posture conditions.

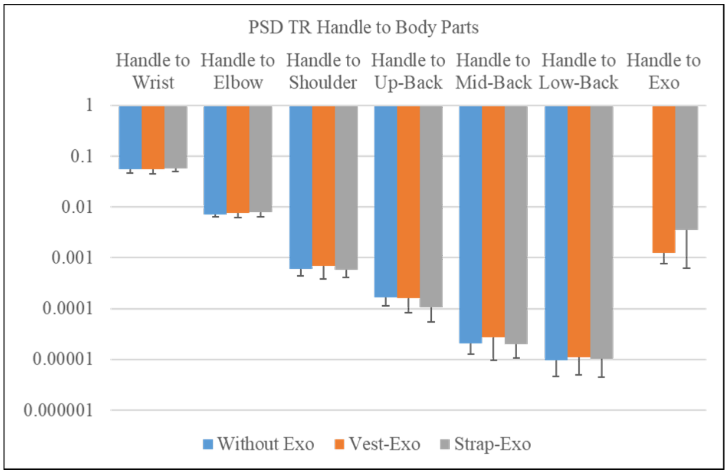

Figure 3. Exoskeleton effect on transmissibility.

Figure 4 shows normalized EMG data under three Exo conditions, respectively. Most muscles examined exhibited lower activities when wearing ArmExos. The agonist muscle activities in the overhead posture were higher when compared to the front-of-body posture. Antagonist muscle activities tended to increase with vibration turned on.

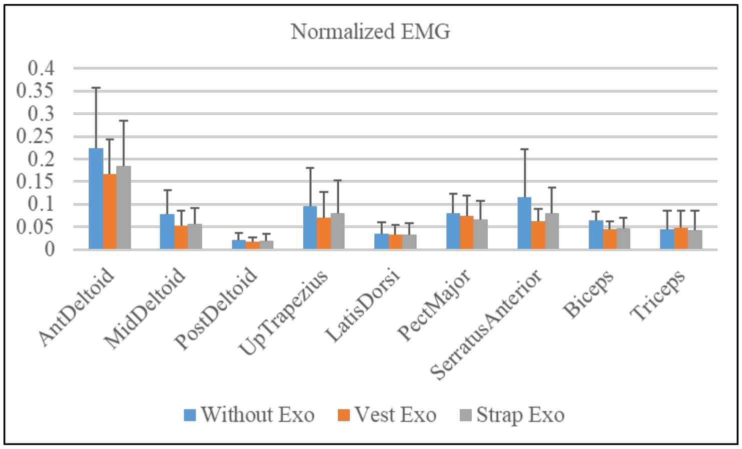

Figure 4. Exoskeleton effect on shoulder muscle activities.

In the present study, the coupling forces were controlled (e.g., same average values). However, the variations of the coupling forces as represented by the standard deviation (SD) of the data demonstrated the peak-to-peak response. Figure 5.a shows that the exoskeleton effect on peak-to-peak coupling force was minimum. As expected, the existence of vibration increased the peak push force significantly, indicating a higher peak mechanical load to the body (Figure 5.b).

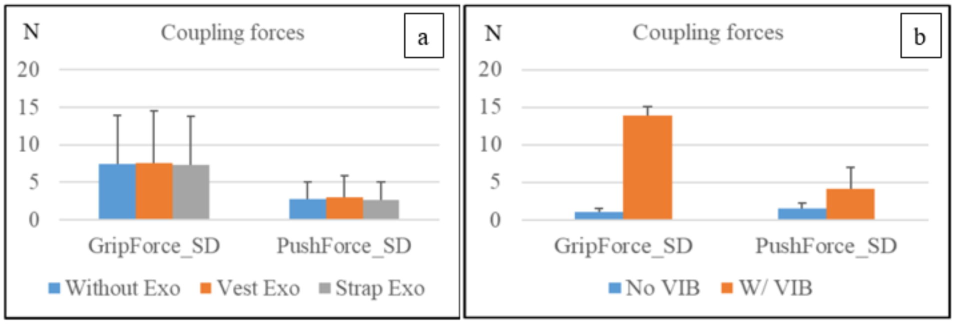

Figure 5. Exoskeleton effect (a), and vibration effect (b) on peak-to-peak coupling forces.

Discussion and Conclusions

The primary aim of this thesis research was to collect preliminary data to assess the combined effects of overhead posture and use of power hand tools on effectiveness of ArmExos. The first observation made on in the present study is the amplitude of VT decreased drastically along the arm and the spine based on the distance of the body parts from the shaker handle. The trend of VT response with respect to distance from the shaker handle was also reported previously. Xu et al. (2017) reported peak response at the frequency of 7 Hz and 12 Hz for the upper arm, 7 Hz and 9 Hz for the shoulder, 6 Hz and 7 Hz for neck and back in the front-of-body vibration. Except the neck, these values are similar to the front-of-body posture in the present study. The overhead vibration posture examined in the present study showed that there was a significant shift in peak VT frequency at the shoulder when compared to the front-of-body posture. The related health effect remains to be investigated. Regarding the exoskeleton effect, there is a large body of literature examining performance of ArmExos in overhead tasks. However, few studies examined the overhead tasks with power hand tools simultaneously. This was the primary reason to conduct the present study. The major finding of the present study was that wearing Exo had minimal effects on VT except at the wrist joint where the peak VT value in the frequency domain decreased significantly with ArmExos.

In present study, the biggest increase in muscle activity was observed in the anterior deltoid and the upper trapezius when compared to the front-of-body posture. These results are consistent with literature findings. Rohmert et al. (1989) examined arm and shoulder muscle activity in overhead vibration and found that the upper trapezius muscle had significant increase in activity in the overhead posture. Kim et al. (2018) examined overhead drilling and showed muscle activities for anterior deltoid, middle deltoid, and descending trapezius were greater in the overhead tasks comparing with the shoulder height task. In the present study, there was a decrease in activity in most shoulder muscles with ArmExos, consistent with the literature (Kim et al., 2018). However, existence of vibration was not found to affect muscle activity much with only a slight increase in some muscles.

Regarding the coupling forces, the peak-to-peak coupling forces as calculated as SD over the 12 seconds of recordings showed that overhead posture with vibration turned on resulted in a higher push force detected at the subject feet. These findings indicate that there was an increase in mechanical load in the body under the overhead condition and under the vibration turned on condition. There is no literature specifically looks at the peak-to-peak coupling force.

In summary, posture and exoskeleton conditions had little effect on VT along the arm and the spine. The shoulder muscle activity was more significant in the overhead posture, especially for the anterior deltoid and upper trapezius. The effects of Exo and vibration conditions on muscle activities showed promising results as expected, though shouldn't be over interpreted. There was a moderately higher peak push force for the overhead posture. There were a significantly higher peak grip force and a moderately higher peak push force with vibration turned on. These results suggest that power tool use in the overhead posture may increase mechanical load in the body. Future studies with a larger sample size are needed to validate the findings of the present study.

Acknowledgments

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