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Study Protocol to Analyze The Effects of Posture and Exoskeleton on Human Exposure to Hand-Transmitted Vibration

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ABSTRACT

STUDY PROTOCOL TO ANALYZE THE EFFECTS OF POSTURE AND EXOSKELETON ON HUMAN EXPOSURE TO HAND-TRANSMITTED VIBRATION

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Exposure to power hand tool-generated vibrations may lead to several health disorders collectively known as hand-arm vibration (HAV) syndromes. Power hand tools are often used in overhead postures in the manufacturing and construction industries. However, HAV risks are examined in the front-of-body posture in the existing safety standards and guidelines. Therefore, it is important to understand the effects of overhead working posture on vibration transmissibility (VT) in the upper extremities (UEs) and the spine. Secondly, there is a rising trend of using occupational exoskeletons (Exos) in the manufacturing and construction industries, especially involving overhead work with power hand tools. However, the role of Exo in VT in the body has not been examined systematically. The primary aim of the present study was to create a laboratory study protocol to examine the combined effects of overhead work and the use of Exos on VT in the body. The extended random vibration spectrum (3 Hz – 1600 Hz) modified according to ISO 10819 (2013) was generated using an electromagnetic shaker. Same as ISO 10819 (2013), the coupling forces with live feedback were set at 30 N for the grip force and 50 N for the push force, respectively. Acceleration was assessed at the wrist, elbow, shoulder acromion on the right arm and at the C7, T10, and L3 levels of the spine using triaxial accelerometers. Acceleration was also assessed at the shaker handle and the right arm-supporting link of Exos. In addition to acceleration, activities from 9 muscles surrounding the shoulder area were examined using surface electromyography (EMG) to aid our understanding of related health effects. A high-throughput maximum voluntary contraction (MVC) protocol was developed for EMG data normalization. The present study employed a nested design with working posture as the level 1 factor (overhead and front-of-body postures), Exo condition as level 2 (Without Exo, Vest-type Exo, and Strap-type Exo), and vibration condition as level 3 (no vibration immediately followed by vibration turned on in one testing run). Three right-handed male subjects were recruited to validate the study protocol. Spectral analysis of the shaker acceleration data suggest that the shaker system can deliver random vibration more reliability above 7 Hz. Circular plastic adaptor bases for accelerometer placement on the skin could help to prevent excessive pressure over the skin and possible adverse effects. Descriptive results indicate that the acceleration level and VT decreased drastically along the arm and the spine based on the distance of the body parts from the shaker handle. Posture and Exo 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 HAV 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.

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BY

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DEDICATION

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CHAPTER 1: INTRODUCTION

1.1 Background

Prolonged exposure to vibrating hand tools can lead to a collection of health problems generally referred as hand-arm-vibration syndromes (HAVS). HAVS can cause irreparable disabilities if left untreated, as well as heavy financial impacts. Safety standards and guidelines have been developed to protect against HAVS, such as ISO 5349, ISO 10819 (ISO 5349-1, 2001; ISO 10819, 2013). The exact mechanisms induced HAVS remains to be full understand due to complex interactions between the hand-arm structure with vibration stimuli. (ISO 5349-1, 2001; Marchetti et al., 2017; Sakakibara et al., 1986). HAVS generally fall into three categories: 1) peripheral neuropathy such as carpal tunnel syndrome (entrapment neuropathy), 2) vascular disorders mostly referred to Raynaud's phenomenon, or vibration-induced white finger (VWF) and, 3) musculoskeletal disorders (Bovenzi, 1998; Griffin, 1997; ISO 5349-1, 2001; Nilsson et al., 2017; Palmer et al., 2001; Saha & Kalra, 2016).

Peripheral neuropathy: tingling, numbness, diminished tactile sensitivity in fingers, and loss of dexterity can develop when working with vibratory tools (ISO 5349-1, 2001). Hand-transmitted vibration can also lead to sensorineural disorders such as carpal tunnel syndrome (CTS) (ISO 5349-1, 2001).

Vascular disorders: vibration white finger syndrome, also known as Raynaud's phenomenon, is regarded as the hallmark of HAVS (Xu et al., 2019). The syndrome is related to interruption of blood flow to the fingers (ISO 5349-1, 2001). Other symptoms can also appear, such as cyanosis or blanching in the skin resulting in a significant decrease in tactile sensation and dexterity (Voelter-Mahlknecht et al., 2008).

Musculoskeletal disorders: exposure to shock and low-frequency vibration (below 50Hz) with high magnitude, such as use of pneumatic percussive tools, can lead to wrist and elbow osteoarthrosis, and ossifications at tendon insertion' areas, especially at the elbow. Exposure to mid or high frequency vibration can lead to bone and joint degeneration in the upper limbs, muscular weakness, and loss of grip-strength (ISO 5349-1, 2001).

1.2 Objectives

There are several physiological and physical parameters, which are related to the severity of hand-transmitted vibration, such as magnitude, frequency, direction and, duration of vibration, area of contact with vibration, contact or coupling force (grip force and push force), finger, hand and arm posture, and environmental factors (e.g. temperature) (Fattorini et al., 2016; Griffin, 1997). To address the knowledge gaps in HAV transmissibility, the present study focused on assessment of posture effect on hand-transmitted vibration in the upper extremity. Vibrating hand tools are often used in the overhead postures and the front-of-body postures. However, current safety standards only assess HAV in the front-of-body posture. Considering the prevalent shoulder injuries caused by working in the overhead postures in many occupations, it is important to investigate the effects of working posture on vibration transmissibility (VT) in the upper extremities (UE) and the spine. Additionally, there is an increasing trend of using occupational exoskeletons (Exos) in industries especially involving overhead tasks with vibrating hand tools. So far, the effect of Exo in VT in the body has not been systematically evaluated. Therefore, the main purpose of this research is to develop a laboratory study protocol to investigate the combined effects of overhead posture and wearing Exos on VT. Additionally, activities of shoulder muscles were examined to aid the understanding of related health effects. Furthermore, coupling forces including grip force and push force were analyzed to understand biomechanical load on the body due to vibration propagation.

1.3 Literature Review

Many studies investigated effect of posture on VT. Most of them studied vibration exposure in the front-of-body posture while few studied in the overhead posture. On the other hand, there are many studies examined the overhead tasks, though in the absence of vibration.

1.3.1 Hand-Arm Vibration in Overhead Working Postures

Overhead tasks are work with elevated arms with elbows above mid-chest or above shoulder (Grieve & Dickerson, 2008; Sood et al., 2007). Working in an overhead posture often lead to shoulder musculoskeletal injuries. Shoulder injuries can cost an average of 12 days of absence from work for rehabilitation process (Grieve & Dickerson, 2008).

Grieve and Dickerson (2008) reviewed physiological and biomechanical effects and shoulder and upper arm movement in an overhead work (Grieve & Dickerson, 2008). High levels of intramuscular pressure, which can limit blood circulation in muscles and develop fatigue, is linked to the shoulder elevation. Additionally, workers experience higher levels of heart rate and blood pressure in an overhead work task and increased fatigue when compared to a front-of-body task. Fatigue impairs shoulder kinematics and function in overhead work that may result in injuries such as Supraspinatus impingement syndrome. Generally, arm height, hand load, work duration, horizontal distance to the hand load, fluctuation of hand force, repetitive tasks are the risk factors for shoulder injuries.

Rohmert et al. (1989) examined arm and shoulder muscle activities of six subjects exposed to sinusoidal vibration (frequency at 30 Hz and acceleration at 40 m/s^2) created by an electrodynamic shaker (Rohmert et al., 1989). The couple forces were set at 50 N for push force and 100 N for grip force. The duration of vibration exposure was 5 min. The postures included (1) overhead ceiling work (shoulder flexion α= 110 ° and elbow flexion β=70°), (2) wall work in a standing posture (shoulder flexion α=60 ° and elbow flexion β =70°), and (3) floor work in a bending posture (shoulder flexion α=90 ° and elbow flexion β =0 °). EMG was collected from 5 muscles (M. extensor carpi radialis brevis, M. flexor carpi ulnaris, M. biceps brachii, M. trapezius pars descendens, M. infraspinatus) based on clinical reports for common shoulder and neck injuries. The upper trapezius showed the greatest activity in all three postures. Also, vibration exposure led to increased EMG index for most muscles in three postures. Based on the theory of tonic vibration reflex phenomenon, it was reasonable to consider vibration as a major factor associated to shoulder and neck injuries.

Maciukiewicz et al. (2016) evaluated upper arm muscle activities in overhead drilling tasks under a variety of conditions (Maciukiewicz et al., 2016). The drilling tool was not on power in order to removing the effect of vibration on force. Electromyography (EMG) of anterior deltoid, middle deltoid, upper trapezius, infraspinatus, supraspinatus, and lumbar erector spinae were obtained. Muscle activities for upward direction was higher than forward direction and the maximum difference was at maximum distance from point of exertion i.e. 45 cm (about 14%). Muscle demand increased as the height of the point of exertion increased. Also, standing posture increased muscle activities for 30 cm and 45 cm point of force exertion form the body but there was negligible difference for the seated posture. There was a small increase in activities of upper trapezius and infraspinatus when using both hands for drilling, while middle deltoid and supraspinatus of dominated hand showed lower activities since load distributed bilaterally.

1.3.2 Hand-Arm Vibration in Front-of-Body Postures

In Adewusi et al. (2010), VT to the wrist, elbow (near the joint on the forearm, and upper-arm), and shoulder were measured in 2 different postures (bent-arm elbow i.e. joint 90°, and extended arm elbow i.e. joint 180°) (Adewusi et al., 2010). Six subjects were exposed to 2 magnitudes of random excitation (with frequency range 2.5 Hz to 2500 Hz, and constant acceleration a_{hw}=2.65 m/s^2, and 5.25 m/s^2). This experiment explored 9 combinations of grip forces, and feed forces. The results showed that with increasing the distance between the measurement location, and the driving point, VT would decrease. Also, for frequencies less than 25 Hz, hand-arm structure in the 180° elbow posture amplify the VT to the upper-arm. However, for frequencies more than 25 Hz, in the bent-arm, decrease in the VT was more than the bent-arm posture excluding at the shoulder. This proved that transmissibility magnitude for the bent-arm is less than that for extended-arm posture for frequencies below 25 Hz which showed that working in the extended-elbow posture can cause more muscle activity, and fatigue. Further, the present study concluded that the grip force changes are more related to the vibration transmitted to the forearm, whereas push force variations can be an influential factor for the dynamic responses of the whole hand–arm structure.

Aldien et al. (2006) has assessed the effect of posture on biodynamic response of hand-arm structure in 1D vibration exposure (z-axis) (Aldien et al., 2006). Aldien conducted this research for 7 subjects in 2 postures (90° elbow angle, and 180° elbow angle). In the frequency range of 8 Hz to 1000 Hz, 2 levels of random excitation (a_{hw}=2.5 m/s^2, and 5.0 m/s^2) and 3 cylindrical handles with difference in diameter (30 mm, 40 mm, 50 mm) were tested. Three levels of grip forces (10 N, 30 N, 50 N), and three levels of feed forces (25 N, 50 N, 75 N) has been selected. The results compared apparent mass (APMS), driving-point mechanical impedance (MPDI), and absorbed power for 2 postures. In lower frequencies (below 30 Hz), the magnitudes of mechanical impedance and apparent mass, and absorbed power for extended arm were higher than those levels for flexed forearm posture. According to the result of this study, working with extended forearm can increase risk of upper arm injury.

Xu et al. (2017) has conducted an experiment to assess VT from handle to upper arm, shoulder, neck, back, and head (Xu et al., 2017). The vibration was transferred to both left and right hands using a dual handle with the frequency range of 4 Hz to 400 Hz. A laser vibrometer (for upper arm, shoulder, neck, and back), and 3 accelerometers (for forehead and both wrists) were used to determine vibration transmitted to the structures. In this research, measurements were obtained in 2 different postures (elbow angle 90° and 120°). Combination of constant grip force 10 N and 3 levels of feed forces (50 N, 75 N, and 100 N) for 1.1g input vibration were assessed. And, only 75 N push force for 0.6g input vibration has been tested. The results showed that the resonant frequency for the wrist was at around 20 Hz, for the upper arm was at 7-12 Hz, for the shoulder was 7-9 Hz, and for the back and neck were at 6-7 Hz. Transmissibility at the shoulder in 90° elbow angle had a higher magnitude than 120°, while at the upper arm, the magnitude was the same or marginally higher for 120°. Also, while the elbow flexed 90°, the trend showed a second peak at the shoulder around 20 Hz, but not for the wrist and upper arm. At the wrist, the resonant peak for 90° was higher with 50 N feed force similar to 75 N push force, and 120° posture was slightly higher with 100 N push force.

Kihlberg (1995) has investigated dynamic response of hand-arm structure exposed to 2 vibration types (impact hammer and grinder) (Kihlberg, 1995). Relation between dynamic response (including driving point impedance, and transfer function from handle to finger, wrist, and elbow) and vibration type or frequency has been explored. Energy absorption per time (dissipated power) in the structure, and 3 grip forces (20 N, 40 N, 75 N) together with 2 push forces (No push force, 100 N) conditions effects were also assessed. This experiment was performed for fifteen subjects, and vibration direction was along the forearm with elbow angle about 110°. The study found that there were not discrepancies in dynamic response between 2 types of excitation when the rest of conditions are the same. Also, in frequencies below 50 Hz, elbow and shoulder joints exposed to higher load than frequencies above 100 Hz (which can exert higher loads on the hand and fingers).

Also, Marchetti et al. (2017) has evaluated vibration transmitted to the elbow (flexed 90°) along a forearm direction with excitation range of 6 Hz to 500 Hz produced by a shaker (Marchetti et al.2017). For 34 participants, 3 levels of grip forces have been tested (20%, 30% and 40% of the maximum voluntary contraction, or MVC, which was referred to the maximum value of 3 trials of measured maximum grip force on the handle). The VT at the elbow was obtained using a laser vibrometer. The results showed that the first resonant peak at 8 Hz is not sensitive to the grip force change, but for higher frequencies, the second resonant peak (23 Hz to 34 Hz), and VT ratio will be amplified by rising the grip force. After the second peak, the transmissibility will reduce with a higher slope by increasing the frequency.

Pan et al. (2018) has performed two experiments to investigate the effects of coupling force and VT on wrist, forearm, and upper arm in the frequency range of 10 Hz to 40 Hz (Pan et al., 2018). In the first experiment, VT to the wrist, forearm, and upper arm was measured using 4 discrete sinusoidal vibrations (10 Hz, 16 Hz, 25 Hz, and 40 Hz), while grip force was increased from 0 to 150N. Additionally, measurement of VT to this hand system obtained under a random excitation in the frequency range of 4 Hz to 500 Hz, and 5 levels of grip force (15 N, 30 N, 45 N, 60 N and 75 N), and a combination of grip, and feed force (30 N grip and 50 N push). This experiments proved that by increasing the grip force in each frequency, transmissibility rises to a peak then reduces. However, the results for two types of excitations followed the same trend which showed transmissibility was not sensitive to the types of input excitation.

1.3.3 Use of Occupational Exoskeletons (Exos)

Nowadays, exoskeletons technology can be a beneficial approach to reduce risk of occupational injuries especially in awkward postures like overhead tasks. The exoskeleton generates a supportive torque that can reduce muscle demand and fatigue, and therefore elevate human performance in task activities (Alabdulkarim et al., 2019; Yin et al., 2020). According to their mechanisms, there are two categories of exoskeletons: passive and active. Springs and dampers are the central part of passive exoskeletons, whereas active exoskeletons use actuators (e.g. motors, hydraulic, pneumatic controls, etc.) to create supportive power to the body (Alabdulkarim et al., 2019; Yin et al., 2020).

McDowell et al. (2019) has investigated the influence of 3 passive exoskeleton vests on VT of the wrist, shoulder, behind the ear of participant exposed to a vibrating handle of a shaker (McDowell et al., 2019). The accelerations were measured at the waist, shoulder, and upper arm frame of exoskeleton (with the extended frequency range of 5-1600 Hz). Front-of-body posture with elbow angle of 120° was used and coupling forces were controlled in the range of 30N grip and 50N push. This experiment evaluated minimum and maximum support of 3 exoskeletons plus 2 no-engaged options for two exoskeletons as well as a condition of No-Exo. The preliminary results showed that in the frequency range of 20 Hz to 50 Hz, the use of exoskeletons with maximum support, attenuated the vibration transmitted to the wrist; however, acceleration transmitted to the shoulder intensified. In addition, acceleration data for the upper arm, shoulder, and waist of the Exo's frame showed an increasing trend by raising the support except for Exo1 at the waist (that experienced a higher level of acceleration at low/minimum level support).

Yin et al. (2020) has performed an experiment to investigate a Passive Upper-Limb Exoskeleton (PULE) performance and evaluate physical demands in the overhead tasks (Yin et al., 2020). 15 male participants operated bolt installation using an impact wrench, in 3 different overhead height levels (low, medium, high), and 2 conditions of with and without the Exoskeleton. The study measured activities of four muscles (anterior deltoid (AD), mid deltoid (MD), descending trapezius (TR), and triceps (TB)) from both sides of the body using surface electromyography. Additionally, rate of perceived discomfort (RPD) for the neck, shoulders, upper arms, forearms, upper back, waists, and legs were assessed. The results are consistent with the assumption that assist of PULE exoskeleton may cause less muscle activities and discomfort comparing non-exo condition (especially for RAD, RMD, RTB, LAD, LMD). Therefore, wearing PULE lead to less fatigue and following risk of upper-limb disorders. This effect was significant (%51.3 reduction of discomfort) for high height level. Moreover, oral feedback of participants in the present study prompted demand of further investigation of long-term effects of exoskeleton on the body especially for trunk.

Maurice et al. (2020), evaluated effectiveness of a commercial passive upper-limb exoskeleton, PAEXO, in an overhead drilling task with elbow angle 90° (Maurice et al., 2020). This research focused on several objective and subjective factors to assess PAEXO performance for 12 subjects, including electromyography of anterior deltoid and erector spinae muscles. The EMG measurements showed the effectiveness of PAEXO in reducing the risk level for shoulder in overhead tasks due to reduction in muscle activity for anterior deltoid (the main agonist muscle in overhead tasks) by 55 percent, and no-extra strain around erector spinae.

Kim et al. (2018) run an experiment for further investigation of strengths and weaknesses of using EksoVest™ exoskeleton in shoulder muscle activities, perceived discomfort, and task performance (Kim et al., 2018). The Ekso Vest generates a supportive torque changing with arm elevation, and it can be on/off by user, and the model used in the present study had neck and back pads and an adjustable mechanism for trunk. This research has been done by 12 subjects and performed 3 overhead tasks including, overhead drilling (light and heavy levels) and light wires connecting. Also, 2 heights conditions (1- hand at the level of shoulder, and 2- an overhead height) as well as with and without exoskeleton conditions have been tested. Electromyography of anterior and middle deltoid, descending trapezius were recorded. The results showed muscle activities for overhead posture was higher than shoulder height, and muscle activities in wiring connection were less than drilling task. Use of exoskeleton caused significant reduction of muscle activities in overhead posture comparing with shoulder task.

1.3.4 Acceleration Measurement and Accelerometer Attachment

In purpose of accurate measurement of the vibration transmitted to the body, accelerometers should be positioned rigidly close to the bony area on the target location such that not shaking due to resiliency of the skin (skin artifacts) or poor connection with the surface to prevent from changes in frequency peak (like DC shift or filtering high frequencies due to using a soft or spongy tape between the sensor and the skin), or misalignment error (Wasserman, 1987). Accelerometer wires should be strain relieved and taped to the surface (skin here) to prevent the effect of noise on measurements by the vibration of the wire (Reynolds et al., 1984). According to Rasmussen (1982), adapters designed for positioning the accelerometers on the surface should have specific thickness and be lightweight such that they have a flat frequency response (transfer function) from 5 Hz up to 1500 Hz and have no significant resonance peak in this spectrum to prevent from transferring high levels of vibration to the accelerometer (Rasmussen, 1982). Wasserman (1987) suggests for a perfect sensor attachment, the skin should be cleaned at first using an alcohol pad and attach a piece of stiff carpet double-side tape (Mylar type carpet tape) on the desired bony location and place the accelerometer on top firmly. Then, by using a strip of this carpet tape on top of sensor, secure the accelerometer on the surface (Wasserman, 1987).

Different approaches have been tested to mount accelerometers on the body. Adewusi et al. (2010) used triaxial PCB accelerometers to measure transmissibility at the wrist, shoulder, around elbow joint area (on both forearm and upper arm) (Adewusi et al., 2010). Accelerometers mounted on Velcro strips that firmly affixed at those locations. According to Adewusi et al. (2010), due to the lower mass of muscles and tissues at the wrist and the high-quality method of mounting, its transmissibility measurement is more accurate than upper arm values.

Kihlberg (1995) used Brüel&Kjær type 4374 accelerometers to measure vibration transmitted to the finger, wrist, and elbow, and placed them on top of small circular plastic adapters and taped around the structure to secure them (Kihlberg, 1995). In this study, vibration was generated by an electrodynamic shaker simulating an impact hammer and a grinder. Plastic adaptors were applicable for evaluating impact hammer with 20 Hz to 1000 Hz one-third octave bands, and 60 Hz to 1000 Hz one-third octave bands.

In another study, vibration created by 12 rivet guns and transmissibility to the hand, wrist, and forearm were measured using triaxial Endevco 23 accelerometers, which were glued to a hand-held adapter for hand sensor, and bracelets for wrist and forearm (Kattle and Fernandez, 1999). According to this study, transmissibility to the wrist for frequencies above 200Hz is very small and just affect fingers and hand.

Reynolds and Angevine (1977) recorded sinusoidal vibration transmission to the hand-arm structure for 3 vibration axis (vertical, horizontal, and axial) using a shaker (Reynolds & Angevine, 1977). In this research, subminiature clamped piezo-resistive accelerometers with weight lower than 0.3 grams were mounted using double sided tape on bony landmarks including, 1-Middle phalanx, 2-Proximal phalanx, 3-Third metacarpal, 4-Triquestrum carpal, 5-Styloid process of ulna, 6-Olecranon, 7-Medial epicondyle, 8-Acromion. Accelerometers were tightly secured on the skin using a small foam rubber on top of the sensors and sticking surgical tape around this structure and skin to reduce relative movement.

Pyykkö et al. (1976) used B&K 8304 accelerometers with 0.4grams weight and a plexiglass form (Metal ring with screws) with 34grams to support the accelerometers corresponded to the vibration direction and minimize the effect of vibration response by tissue (Pyykkö et al., 1976). Vibration transmissibilities were obtained at the styloid process for the wrist, the olecranon for the elbow, and the medial epicondylus for the upper arm.

Aatola (1989) evaluated vibration transmitted to the wrist for 3 excitation levels (sweep sine in the range of 10Hz to 400 Hz) created by a handle (Aatola, 1989). Accelerometer B&K 4371 structure placed securely on the styloid process of ulna at the wrist using a system of two pieces of acrylic plate and a hose clamp (weighing 59 grams) while the sensor was screwed to one of the acrylic plates.

Cherian et al. (1996) investigated transmissibility of hand, forearm, and upper arm in the exposure of sinusoidal vibration frequency from 10 Hz to 200 Hz (Cherian et al., 1996). Miniature accelerometers (weight 2.2 grams) were located at the middle finger (ring), forearm (bracelet), and close to the elbow joint at the upper arm side (lightweight aluminum strip tightly attached to the upper arm with the help of an elbow pad).

In this HAV thesis, the acceleration of the spine was also recorded using 3 triaxial PCB accelerometers to assess the effect of hand vibration transmitted to the back (upper back, middle back, and low back).

Kiiski et al. (2008) measured the effect of whole-body sinusoidal excitation by a platform in the vertical direction and in the frequency range of 10 Hz to 90 Hz (Kiiski et al., 2008). Triaxial accelerometers were positioned on the skin of the ankle (left medial malleolus of the tibia), knee (left tuberositas tibia), hip (left greater trochanter), spine (processus spinosus of the third lumbar vertebra or L3-with the exception of subject3 that the processus spinosus of the ninth thoracic vertebra T9 was selected due to lumbar lordosis and prominent paraspinous muscles). The attachment for each accelerometer used double-sided tape and tightened it firmly by an elastic bandage around.

In another research by Tankisheva et al. (2013), whole-body vibration transmitted to the body was examined using 3 vertical sinusoidal vibration platforms (for 4 frequencies conditions: 30 Hz, 35 Hz, 35 Hz, 50 Hz) (Tankisheva et al., 2013). VT was measured for 9 positions on the body including, head-H, manubrium of the sternum-S, vertebra prominens-VP (C7), third lumbar vertebra-L3, anterior superior iliac spine-SISA, greater trochanter-TM, medial condyle of the femur-MC, tuberositas tibiae-TT, and medial malleolus-MM. Triaxial accelerometers were securely adhered to the skin on landmarks using adhesive tape, and bandages were used around cubes and leads to eliminate motion artifacts.

Matsumoto and Griffin (2000) compared transmissibility of vertical whole-body vibration to the head, 3 locations along thoracic vertebrae (T1, T5, T10), 3 points of lumbar vertebrae (L1, L3, L5), the pelvis and left knee, and for 2 standing and seated posture (Matsumoto & Griffin, 2000). Random excitation produced using a platform with a frequency range of 0.5 Hz to 20 Hz. Translational accelerometers used in this experiment were Entran EGA-125-10D model attached on a T-shaped balsa-wood block and adhered to the body using double-sided adhesive tape and adhesive plaster.

CHAPTER 2: METHODOLOGY

2.1 Subjects

For this protocol study, three right-handed, healthy male participants were recruited with age between 18 and 60 and hand size between 7 and 10 (ISO 10819, 2013). A screening questionnaire was used to determine participant eligibility. All participants underwent informed consent process and signed consent document before enrollment. The present study was carried out at the NIU main campus, DeKalb, IL with the IRB approval number HS20-0219.

Because of allergic reaction to the accelerometer attachment on the skin, subject 3 only completed the first study visit. Data collected from the rest two subjects were used for analysis.

2.2 Study Design

A single-group, full-factorial, nested design using within-subject comparisons (Figure 2.1) was employed to investigate 1) VT along the arm and the spine, 2) shoulder muscle activities, and 3) coupling forces when the subjects were exposed to varying HAV conditions. The three main factors in this nested design are: 1) posture as level 1, 2) exoskeleton as level 2, and 3) vibration condition as level 3. For the full-factorial design, or 2 postures × 3 Exo-conditions × 2 vibration conditions, there were a total of 12 testing conditions. Each condition was repeated 3 times, or a total of 36 measurements.

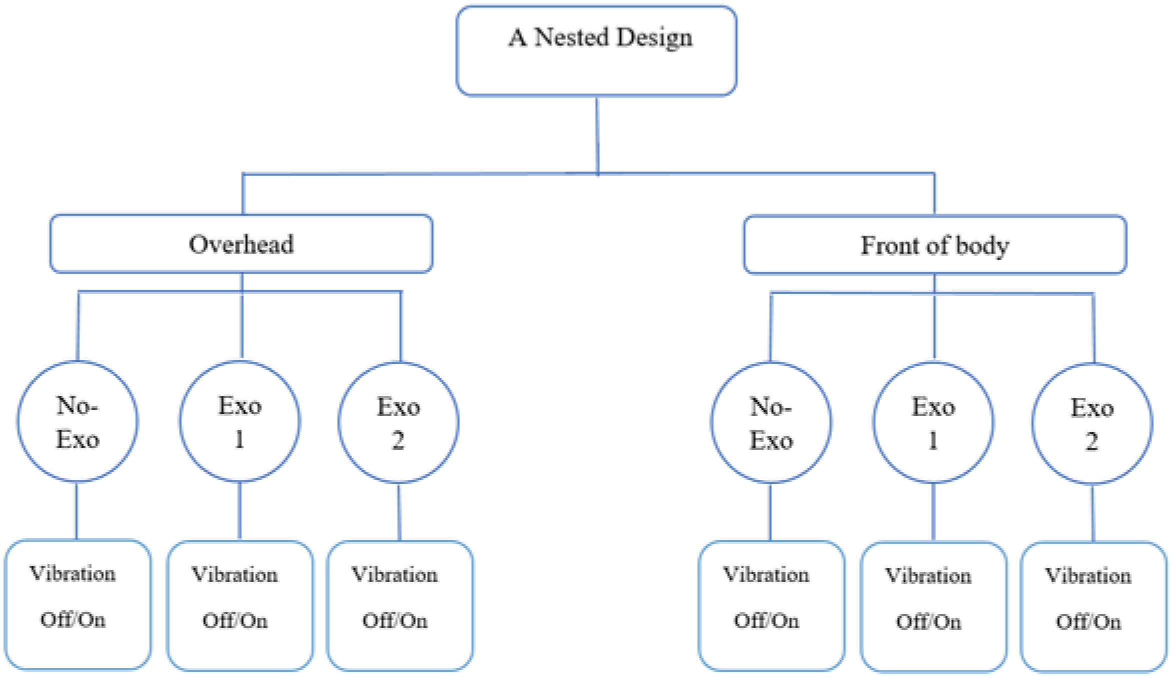

Figure 2.1 The single-group nested study design flowchart.

2.2.1 Level 1 – Posture (2 Conditions):

An overhead posture and a front-of-body posture were examined in the present study. For the overhead posture, both elbow and shoulder were flexed 90° in the sagittal plane (Figure 2.2.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 2.2.b). To keep the arm in the angles defined in the two postures for subjects of varying height, a scissor lift platform was used to adjust subject's standing height. It is noteworthy that the time needed for the overhead shaker setup is about 4 to 5 hours and 1 to 2 hours for the front-of-body setup. Thus two study visits were required to complete the entire study protocol.

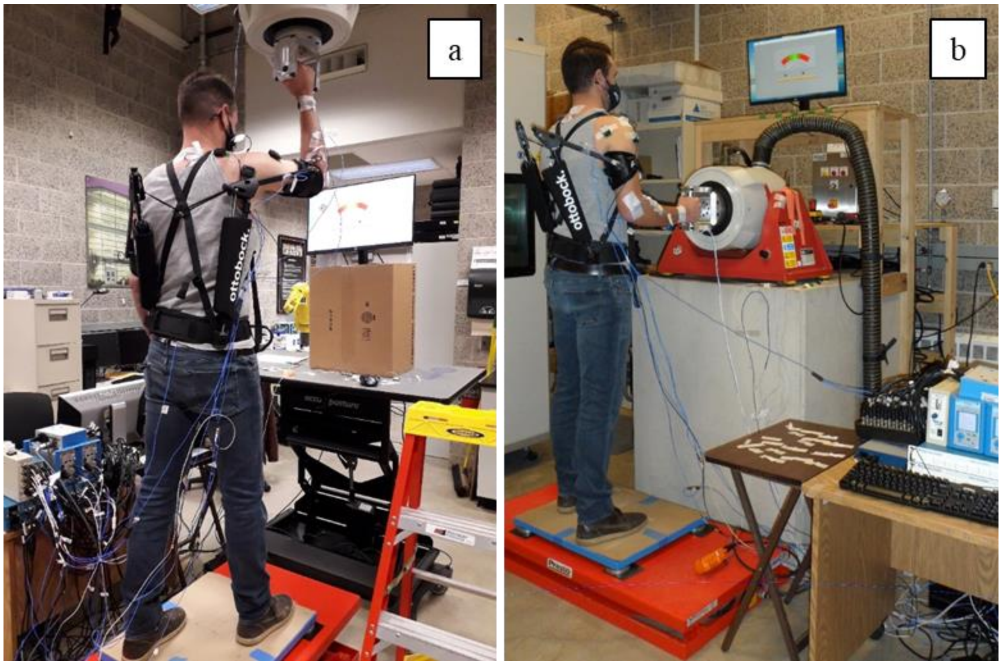

Figure 2.2 Illustration of the overhead posture (a) and the front-of-body posture (b).

2.2.2 Level 2 – Exoskeleton (3 Conditions):

Two commercially available, arm-supporting exoskeletons were used in the present study, including 1) a vest-type Exo – EksoVest, Model V-1.0-0574, Ekso Bionics, Richmond, CA (Figure 2.3.b) and a strap-type Exo – Paexo Shoulder, Model 6ES100=2, Ottobock, Duderstadt, Germany (Figure 2.3.c). A condition of not wearing Exo was also tested to serve as control (Figure 2.3.a).

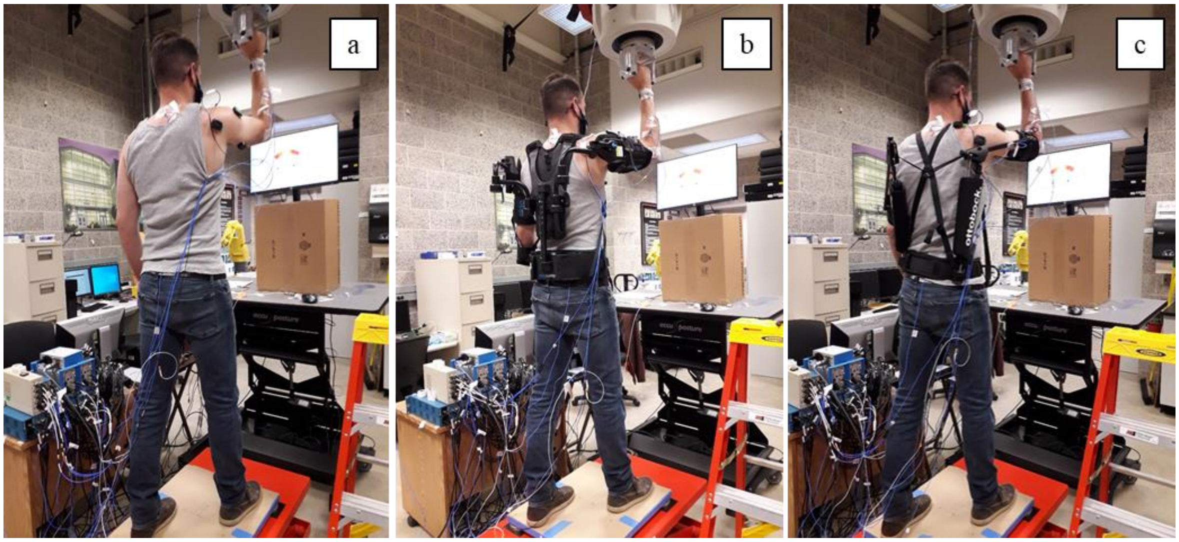

Figure 2.3 Illustration of not wearing exoskeleton (a), wearing a vest-type exoskeleton (b), and wearing a strap-type exoskeleton (c).

2.2.3 Level 3 – Vibration (2 Conditions):

Two vibration conditions were examined in the present study with the no vibration tested first followed by the vibration turned on. The vibration spectrum was generated using an electromagnetic shaker. It took the shaker approximately 1 minute to achieve the designed waveform and amplitude. In other words, there was a one-minute separation between the test with no vibration and the test with vibration.

2.2.4 Test Sequence Randomization

The testing conditions were randomized except for the vibration conditions, of which the two vibration conditions were tested in a single testing run by first with vibration turned off followed by vibration turned on. Therefore, the randomization of testing sequence was only performed between the posture and exoskeleton conditions (2 postures x 3 Exos = 6 conditions).

The testing sequences were generated using a Latin Squares – Williams design. A minimum of 6 subjects are needed for the randomization of 6 conditions as illustrated in Figure 2.4.

Study visit	1	2
SubNo.	OH	FOB
sub1	123	123
sub2	231	231
sub3	312	312

SubNo.	FOB	OH
sub4	321	321
sub5	132	132
sub6	231	213

Figure 2.4 The testing sequences for 6 subjects with posture and exoskeleton condition randomized. OH: overhead posture; FOB: front-of-body posture; exoskeleton testing order such as 132: not wearing exoskeleton (Exo1) tested first, wearing the strap-type exoskeleton (Exo3) tested second, and wearing the vest-type exoskeleton (Exo2) tested third.

2.2.5 Study Activities in One Visit

The two study visits were arranged in the same manner. Figure 2.5 illustrates the study activities in one study visit. The time to complete one study visit was approximately 3 hours, or 6 hours in total to complete the entire study protocol.

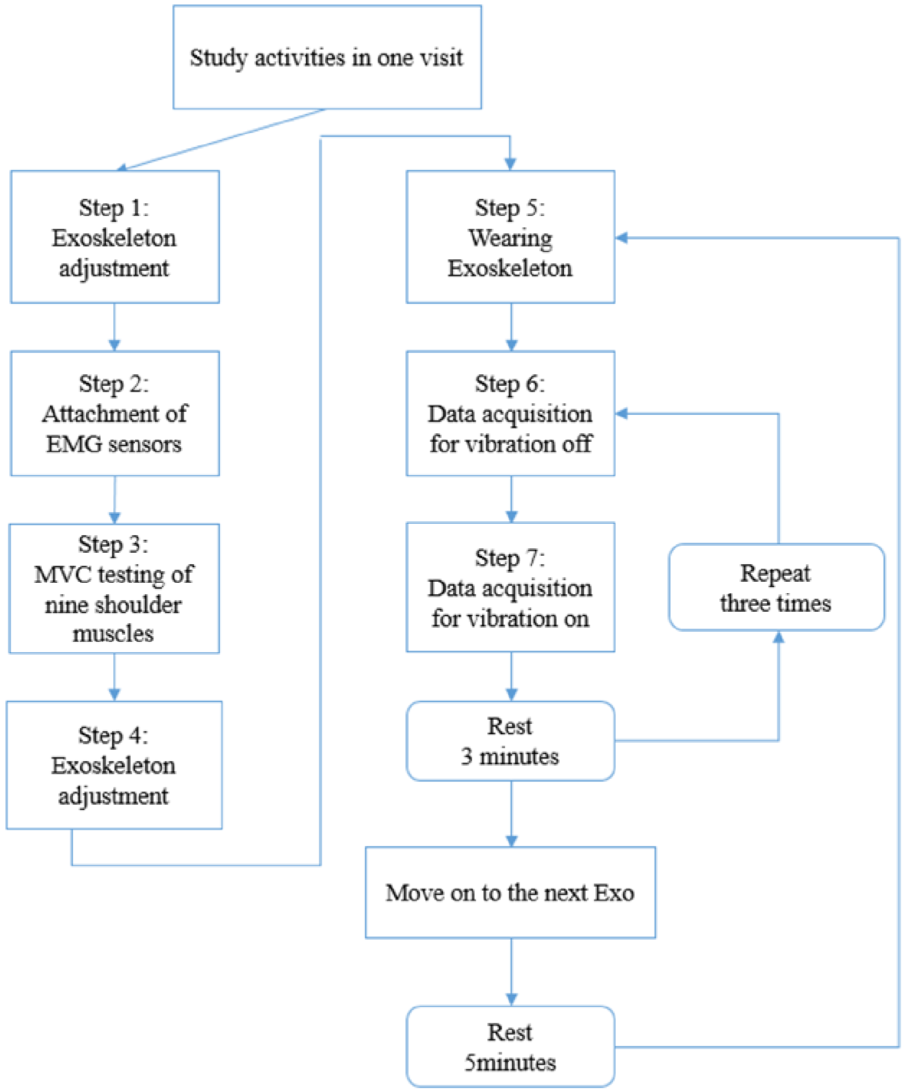

Figure 2.5 Study activities in one study visit.

2.3 Equipment Setup and Experimental Procedures

2.3.1 Shaker System Setup in The Overhead and The Front-of-Body Positions

In the present study the simulated HAV was generated using an electromagnetic shaker system (LDS V651 shaker, Brüel & Kjær, Nærum, Denmark) (Figure 2.6). A vibration control system (VR8500, Vibration Research, Jenison, MI) was used to drive the shaker (Figure 2.7). The controller also received feedback acceleration signal generated from an accelerometer placed inside the shaker handle such that the shaker acceleration can be tightly controlled, for example to produce the designate vibration spectrum.

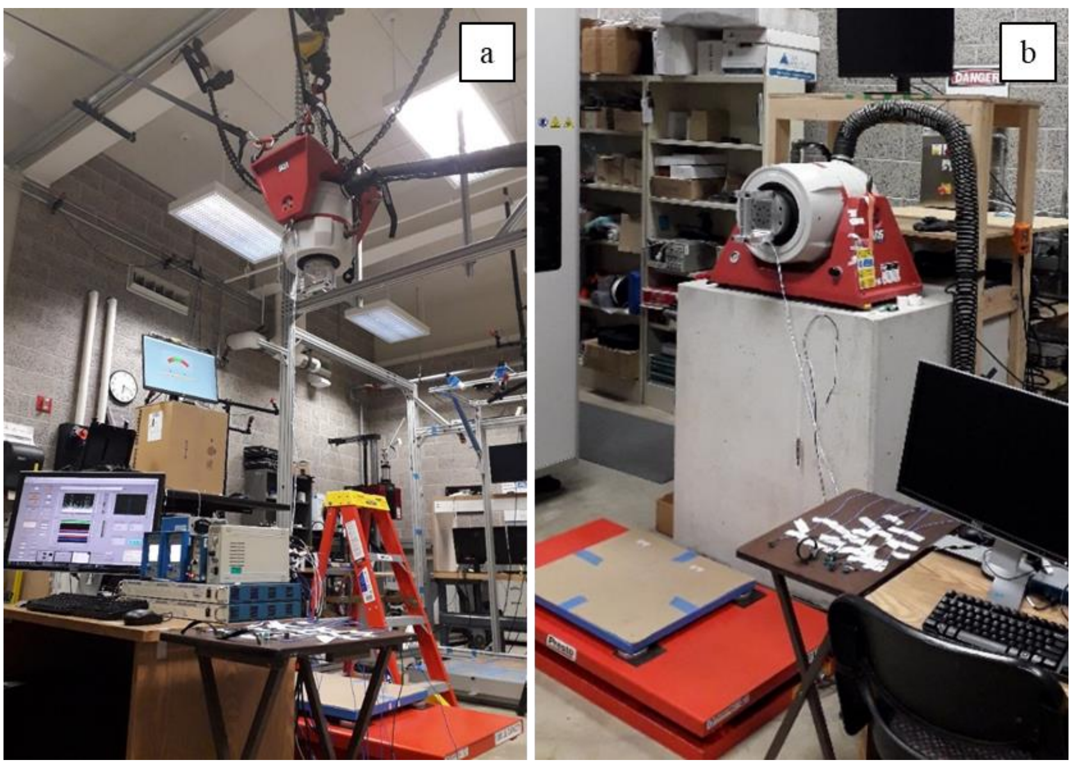

Figure 2.6 Illustration of the electromagnetic shaker setup in the overhead position (a) and the front-of-body position (b), respectively.

Figure 2.7 The VR8500 vibration control system.

2.3.2 Random Vibration Spectrum

In the present study a random vibration spectrum modified from the spectrum defined in the ISO 10819 was used for testing (ISO 10819, 2013) (Figure 2.8). The only difference was the spectrum used in the present study had the lower end frequency extended from 25 Hz to 3 Hz while the upper end frequency remained the same at 1600 Hz. The slope of the extended part was set as same as the slope at 25 Hz.

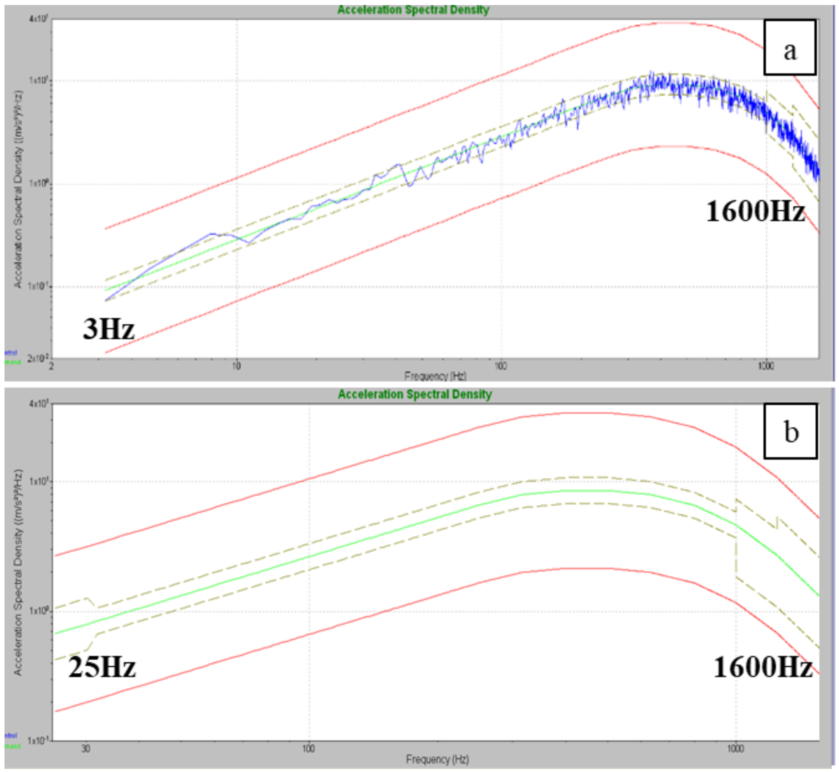

Figure 2.8 Illustration of one testing run of the extended random vibration spectrum (a) and the theoretic spectrum defined in the ISO 10819 (2013) (b).

2.3.3 Acceleration Assessment

To understand vibration transmission 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 Exos. Further a triaxial accelerometer was placed inside the shaker handle. The Z-axis of the shaker handle accelerometer was also used to control the vibration spectrum. Table 2.1 summarizes the models of accelerometers used and associated amplifiers. The accelerometers for the elbow and the shoulder were in miniature forms while the accelerometers in other locations are in regular sizes (Figure 2.9). Accelerometer signals were recorded using a custom-written LabVIEW program (Version 17, National Instrument, Austin, TX). The sampling frequency was set at 5000 Hz.

Table 2.1 Summary of Accelerometer Placement, Models and Amplifiers/Conditioners. PCB: PCB Piezotronics, Depew, NY; B&K: Brüel & Kjær, Nærum, Denmark.

	Sensor location	Model and manufacture	Signal conditioner(s)
1	Shaker handle	PCB 356A12	PCB 483C
2	Wrist	PCB 356A11,	PCB 483C
3	Elbow	PCB 356A01	PCB 483C
4	Shoulder	B&K 4524	PCB 483C
5	C7 spinous process	PCB 356A24	PCB 482A22
6	T10 spinous process	PCB 356A32,	PCB 482M66
7	L3 spinous process	PCB 356A32	PCB 482A05
8	Exoskeleton	PCB 356A12	PCB 482A22, 482M66, 482A05,

2.3.3.1 Accelerometer Attachment to Subject's Body and The Exoskeletons

For the first three study visits, all 3 subjects performed the overhead tests. Except at the wrist and the elbow, rest of the 4 accelerometers were attached to subject's skin directly using double-sided tape (MKR-2S-TAPE, B&L Engineering, Santa Ana, CA) For the wrist, the accelerometer was screwed onto a square aluminum plate (0.8in×0.8in with thickness 0.12in) and then fastened around the wrist using Velcro strips. For the elbow, a rectangular plastic adaptor base (0.71in×0.39in×0.08in) was used to attached the accelerometer to the skin using double-sided tape. All accelerometers were further covered with 2in×3in medical water-proof tape (Cover-Roll stretch – Leukoplast tape, BSN Medical GmbH, Hamburg, Germany) for secure attachment.

Because the subject 3 developed allergic reaction to the accelerometer attachment on the skin, the accelerometer attachment was modified for the remaining of the study. Particularly, 5 3D-printed, circular plastic plates (diameter 0.75in and thickness 0.07in) were used as adaptor bases for the attachment of accelerometers to the skin (Figure 2.9). Superglue (Gorilla Glue Company, Sharonville, Ohio) was used secure the accelerometer to the adaptor base. Circular double-sided tape (MKR-1-1/4C, B&L Engineering, Santa Ana, CA) was then used to attach the accelerometers to the skin. For the wrist sensor, the screw area on the aluminum plate was covered by wax to protect the skin from the sharp edge of the screw. Again, all accelerometers were covered with waterproof medical tape on the top.

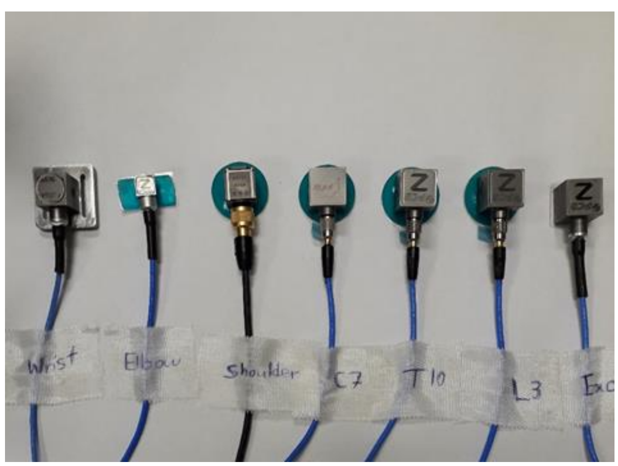

Figure 2.9 sensors mounted on adapters

The Exo accelerometer was attached using either wax for the vest-type Exo or double-sided tape for the strap-type Exo due to different materials covering the area. Similarly, the accelerometer was secured with water-proof tape covered on the top (Figure 2.10).

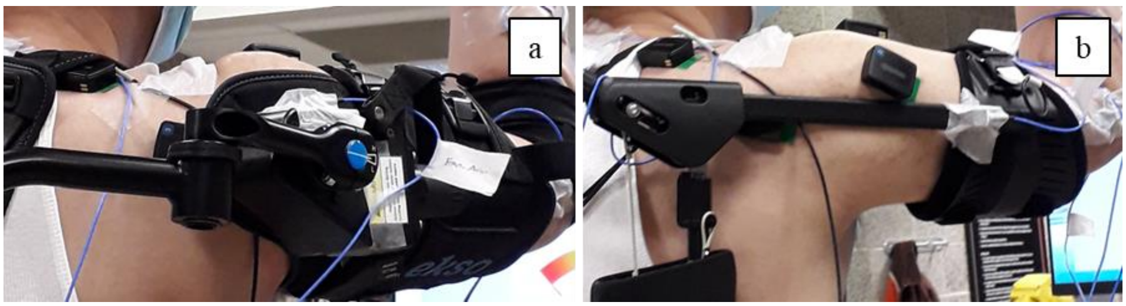

Figure 2.10 accelerometer attachment on exoskeletons' frame Vest-Exo (a), Strap-Exo(b)

2.3.3.2 Accelerometer Adapter Base Validation

The circular accelerometer adaptor bases were fabricated in the middle of the study, thus needed to be validated. A TIRAvib shaker model S51120 powered by TIRA BAA 120 amplifier (TIRA GmbH Schalkau, Germany) and a dynamic signal analyzer SR785 (Stanford Research Systems, Sunnyvale, CA) were used to verify the frequency response of these adapter bases (Figure 2.11). The signal analyzer supplied white noise from 0 Hz to 1600 Hz to the TIRA shaker system in open loop (i.e., uncontrolled random vibration). A uniaxial miniature accelerometer (352A24, PCB Piezotronics, Depew, NY) was used as the reference accelerometer. It was attached to the TIRA shaker using wax. The accelerometer-base combinations were attached to the TIRA shaker using circular double-sided tape. Average frequency response in the Z-axis for all 5 accelerometer-base combinations was recorded for 12.8 seconds at the sampling rate of 8192 Hz and the resolution of 4 Hz (i.e., 400 FFT lines over the 0 Hz - 1600 Hz range).

Figure 2.11 Setup for accelerometer base validation

2.3.4 Surface Electromyography and Muscle Activity

A 16-channel wireless surface electromyography (EMG) system (Trigno, Delsys Inc., Natick, MA) was used to obtain activities of nine muscle (Figure 2.12.a). 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 DELSYS system is equipped with 10 Trigno Avanti EMG/IMU sensors plus 2 Trigno Duo Mini EMG/IMU sensors with analog band-pass filtered between 20 and 450 Hz. The EMG signals were output as analog signals and recorded using a 32 channel, NI-9205 voltage input module (National Instrument, Austin, TX) with a custom-written LabVIEW program (Version 17, National Instrument, Austin, TX) (Figure 2.12.b). The sampling frequency was set at 5000 Hz.

Figure 2.12 The DELSYS Trigno Wireless EMG System (a) and the NI-DAQ 9205 voltage input module (b) for recording muscle activities.

2.3.4.1 EMG Sensor Locations

In the present study, surface EMG sensor placement locations were adapted from Cram et al. (1998), Hermens et al. (2005), and COMRX (1992). Figure 2.13 illustrates the EMG sensor attachment. The details are listed below for each muscle.

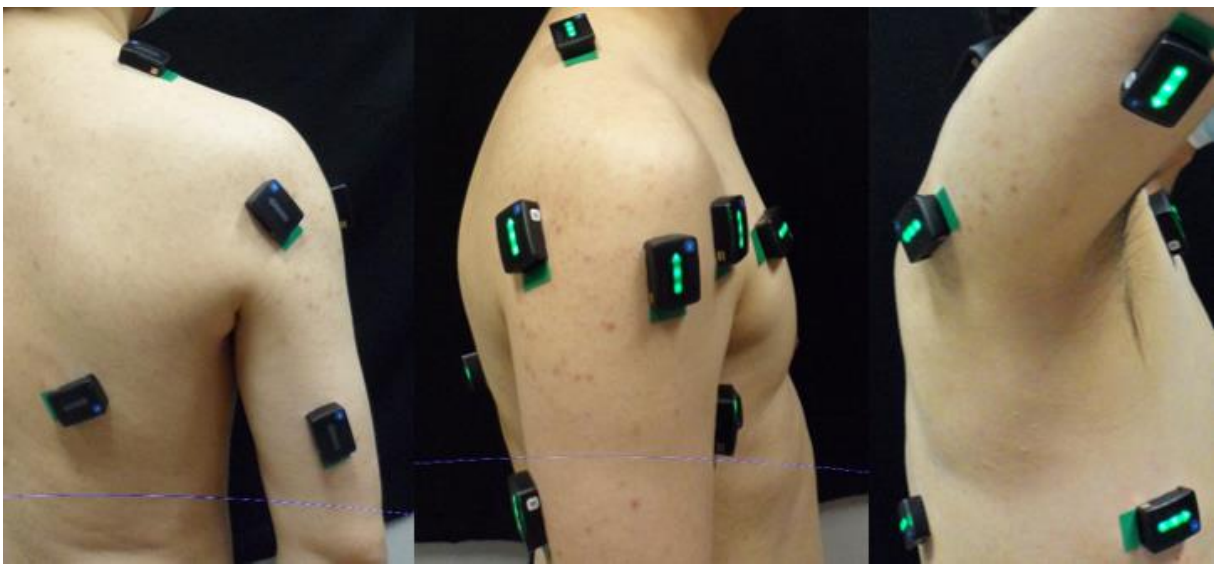

Figure 2.13 Illustration of EMG sensor attachment

Anterior deltoid: the subject was sitting with the arms hanging down in a neutral position and the palm pointing inwards. The EMG sensor was attached to the skin anterior to the acromion, in line with the acromion and the thumb (Hermens et al., 2005).

Medial deltoid: the subject was sitting with the arms hanging down in a neutral position. The EMG sensor was attached in line with the acromion and the lateral epicondyle at the most bulging part of the muscle belly (Hermens et al., 2005).

Posterior deltoid: the subject was sitting with the arms hanging down in a neutral position and the palm pointing inwards. The EMG sensor was attached in the area about two fingerbreadths behind the acromion and in line between the acromion and the little finger (Hermens et al., 2005).

Upper Trapezius: the subject keeps an erect sitting posture with the arms hang down naturally. The EMG sensor was attached at halfway between the acromion and the C7 spinous process (Hermens et al., 2005; Cram et al., 1998).

Latissimus dorsi: the EMG sensor was attached about 4 cm below the inferior tip of the scapula, halfway of the line between the spine and the lateral edge of the torso, oriented in about 25°angle (Cram et al., 1998).

Pectoralis major: while the subject medially rotated the arm against resistance, the EMG sensor was attached in a horizontal direction on the muscle belly of the chest wall that comes about 2 cm outer from the axillary fold (i.e., armpit) (Cram et al., 1998).

Serratus anterior: the subject was asked to flex the right arm against resistance. The EMG sensor was placed in a horizontal direction lower than the axillary area, and anterior to the latissimus dorsi muscle (Cram et al., 1998).

Biceps brachii: the subject sits with the elbow flexed at a 90° angle and the dorsal side of the forearm was horizontally pointing downward. The EMG sensor was attached at 1/3 from the fossa cubit in line between the medial acromion and the fossa cubit (Hermens et al., 2005; COMRX, 1992).

Triceps brachii long-head: the subject was asked to sit with the shoulder at a right angle abduction and the arm flexed 90° with the palm pointing downwards. The EMG sensor was attached at halfway between the line form posterior crista of the acromion to the olecranon (at about 2 finger widths medial to the line) (Hermens et al., 2005; COMRX, 1992).

2.3.4.2 Maximum Voluntary Contraction (MVC) assessment

Shoulder muscle MVC was assessed through 8 movements. These movements were selected according to previous attempts, and some modifications were considered like exerting a resistance by tester instead of using strap (Al-Qaisi & Aghazadeh, 2015; Boettcher et al., 2008). The duration of each movement was set to 15 seconds with 5 seconds for preparation, 5 seconds performing the MVC movement, and 5 seconds to move to the next muscle testing. Therefore, the total recording time was 120 seconds (8×15) for each trial. The procedure was repeated 3 times with 3 minutes rest in between. The maximum value of 3 trials of all eight movements was used as the MVC. Below is the detailed description of each testing movement.

Anterior deltoid: the subject flexed both the shoulder and elbow 90° in the sagittal plane. The subject then pushed the arm up as hard as possible against the resistance applied at the elbow end of the upper arm by the tester.

Medial deltoid and Seratus Anterior: the subject abducted the arm 90° in the frontal plane and flexed elbow 90° with the upper arm and the forearm parallel to the ground. The subject then pushed the elbow up as hard as possible against the resistance applied at the elbow by the tester.

Posterior deltoid: the subject flexed elbow 90°. Also the subject placed one foot in front and one foot behind in order to maintain balance. The subject then pushed both elbow backward as hard as possible against the resistance applied at the elbows by the tester.

Latissimus dorsi: subject placed both hands in fists on the waist and the elbow flexed 90°. The subject then contracted the latissimus dorsi as hard as possible with the intent to extend both shoulders backward and inward against the resistance created by the muscles from the front of the body (i.e., agonist-antagonist cocontraction). The tester paced the hands at the subjects elbows to help stabilizing the posture.

Biceps: the subject flexed the right elbow 90° and internal rotated the right arm towards the body. The subject then placed the left hand over the right hand, pushed the right hand up against the left hand as hard as possible.

Triceps: the subject flexed the right elbow 90° and internal rotated the right arm towards the body. The subject then placed the left hand under the right hand, pushed the right hand down against the left hand as hard as possible.

Pectoralis major: the subject placed the right fist into the left palm in front of the body. The subject then bended slightly forward and pushed the right hand against the left hand as hard as possible.

Upper trapezius: the subject placed the right hand on the side of the head with the head tilted slightly to the right. The subject then lifted the right shoulder upward and inward as hard as possible while contracted the shoulder downward movement muscles at the time (agonist-antagonist cocontraction). The head also provided some resistance to the right hand, though the primary purpose was to stabilize the right arm.

2.3.5 Coupling Forces

To standardize the testing within- and between-subjects, the coupling forces (i.e., grip force and push force) was tightly controlled based on the coupling forces specified in the ISO 10819 (IOS 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) (Figure 2.14).

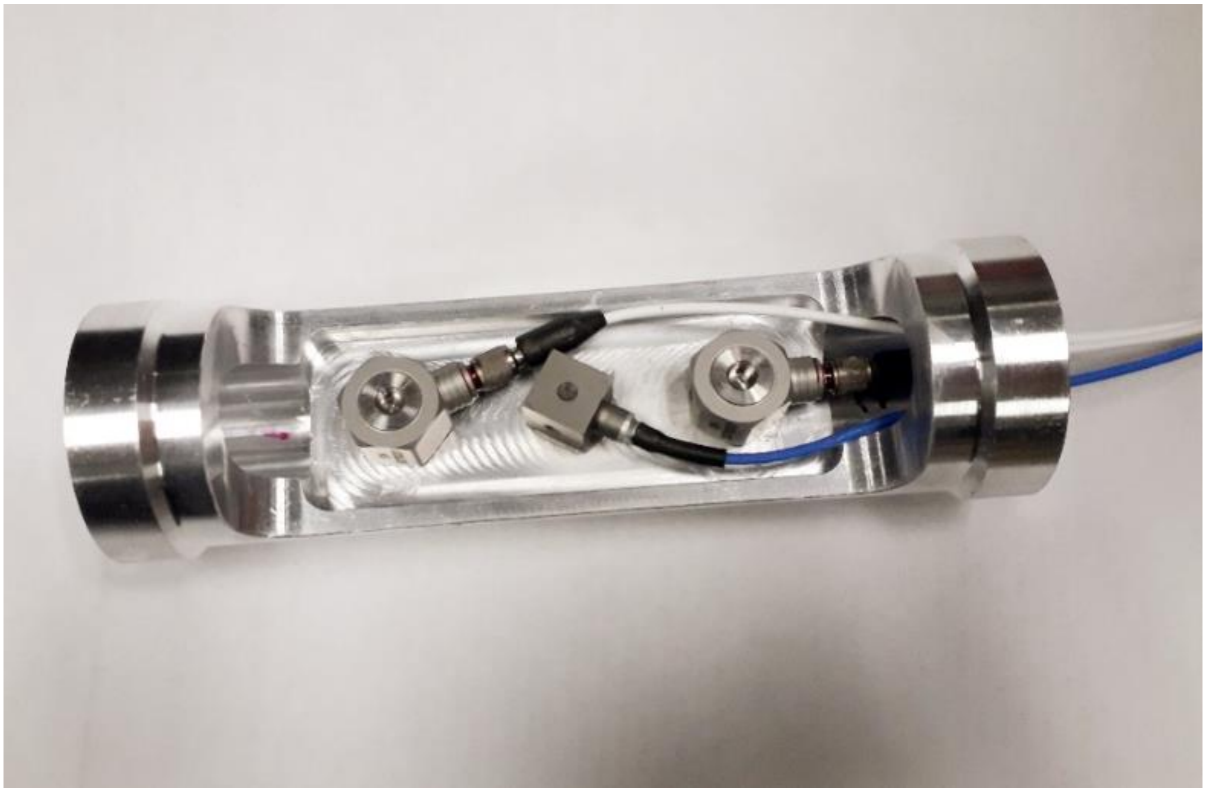

Figure 2.14 The insider view of the instrumented shaker handles showing one accelerometer located in the middle and two uniaxial force transducers located left and right.

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 (see Figure 2.2 and Figure 2.15). 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. Further, 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) (Figure 2.16).

Figure 2.15 A force plate 9260AA and A scissor lift placed under the subject's feet.

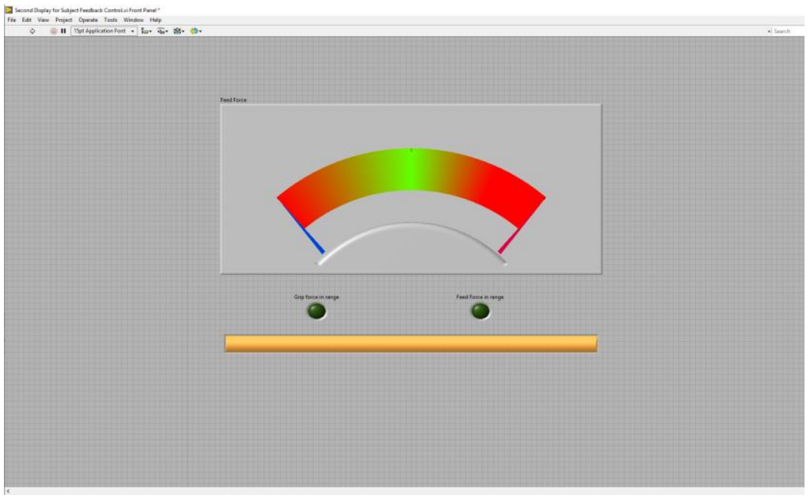

Figure 2.16 Live feedback interface in a LabVIEW environment with the red needle representing grip force and the blue needle representing push force.

2.3.6 Data Acquisition and Signal Processing

In the present study, a custom-written LabVIEW program (Version 17, National Instrument, Austin, TX) with two analog-to-digital converters (NI USB-6363 and NI –9205 National Instrument, Austin, TX) were used for data collection (Figure 2.17). The sampling rate was set at 5000 Hz. The sampling duration was 12 seconds for each testing conditions.

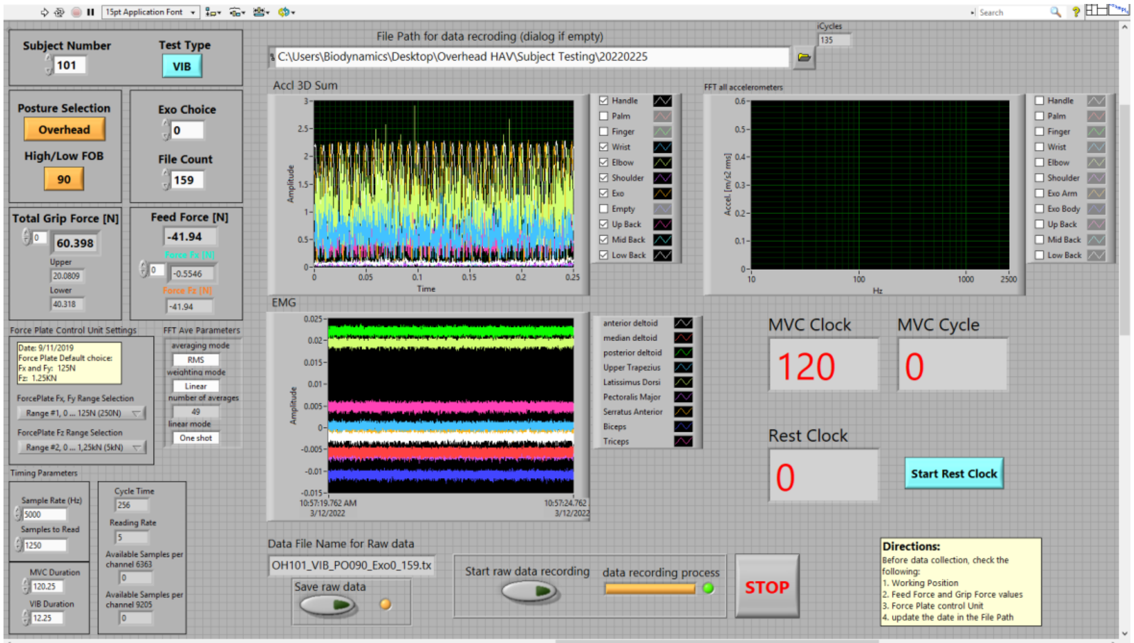

Figure 2.17 LabVIEW program for data collection

2.4 Outcome Measures

2.4.1 Vibration Transmission

In the present study the raw acceleration amplitude in the time domain was calculated as the vector summation of acceleration in the XYZ directions. Since random vibration was used in the present study, VT needs to be calculated using power spectrum density (PSD). Particularly, the pspectrum function in MATLAB was used to obtain PSD from the raw acceleration data. VT was calculated as the ratio of area under the curve of PSD between two locations. The proper frequency range for area under the curve calculation was determined afterwards (see Results section).

2.4.2 Muscle Activity

Raw EMG data during MVC procedures and vibration testing were detrended to remove DC component and then smoothed using RMS with the window size of 0.5sec (2501 data points). A single value was calculated by averaging the 12 seconds of RMS EMG data obtained during vibration. The normalized value was obtained by dividing the average value by the MVC value for each muscle group. Both the raw and the normalized values were used for data analysis.

2.4.3 Coupling Forces

Grip force and push force was averaged over the entire 12-second measurements and used for data analysis.

2.4.4 Data Analysis Plan

Due to the small sample size (n=2) for this study protocol study, descriptive results in mean and standard deviation (SD) were obtained as preliminary data for future studies.

CHAPTER 3: RESULTS

3.1 Study Protocol Validation

3.1.1 Reliability of The Shaker System in Reproducing Random Vibration

In the present study, the random vibration spectrum was modified from the random vibration spectrum specified in the ISO 10819 (2013) by extending the lower frequency boundary from 25 Hz to 3 Hz with the same slope defined at 25 Hz. Since the shaker system is single axial (defined as the Z direction), the PSD for the shaker handle z-axis acceleration was used to examine the reliability of the shaker system in reproducing the extended random vibration. The PSD data show that the reproduction of extended random vibration spectrum was more reliable above 7 Hz due to following observations. First, the PSD values kept increasing as the frequency went lower under 7 Hz (Figure 3.1 a). This is contradicting to the specified extend random vibration spectrum, in which the acceleration should decrease from 25 Hz to 3 Hz continuously. Additionally, there was a high variation of acceleration below 7Hz from subject to subject and from trial to trial (Figure 3.1 b). Based on these observations below 7 Hz, the frequency ranges selected for data analysis in the present study was chosen between 7.3 Hz and 500 Hz for PSD analysis The 7.3 Hz was the MATLAB PSD output frequency value.

Freq	Sub1_OH	Sub2_OH	Sub1_FOB	Sub2_FOB
0	139.0516	27.65799	13.86542	[illegible]
0.610501	132.8535	26.43851	13.256321	[illegible]
1.221001	115.8371	23.09412	11.585867	14.871994
1.831502	92.09973	18.43934	9.2613014	11.853165
2.442002	66.69207	13.47506	6.7844266	8.6363362
3.052503	43.92284	9.049724	4.5827961	5.7783522
3.663004	26.28992	5.647669	2.9030228	3.6010134
4.273504	14.33639	3.364294	1.7961098	2.1704596
4.884005	7.217116	2.023614	1.1737635	1.3702264
5.494505	3.504909	1.341841	0.8890153	1.0076064
6.105006	1.831852	1.05469	0.8009874	0.8995177
6.715507	1.201908	0.975761	0.8072896	0.9145163
7.326007	1.025042	0.997852	0.8486708	0.9766913
7.936508	1.011562	1.067375	0.8991885	1.050416
8.547009	1.044586	1.15733	0.953115	1.1227847
9.157509	1.08743	1.250639	1.0140141	1.1916783
9.76801	1.133777	1.334421	1.0871493	1.2598215
10.37851	1.187171	1.400626	1.1748945	1.3321349
10.98901	1.254465	1.448022	1.2748873	1.4141372
11.59951	1.343303	1.482278	1.3807741	1.510619
12.21001	1.459484	1.513198	1.4849522	1.6246087
12.82051	1.603869	1.550126	1.582	1.7566322
13.43101	1.770148	1.597703	1.6711071	1.9041539
14.04151	1.944939	1.654145	1.7561777	2.0614053
14.65201	2.110724	1.713109	1.8433943	2.220263
15.26252	2.25078	1.768409	1.9374581	2.3727147
15.87302	2.354112	1.819318	2.0386955	2.514405
16.48352	2.418127	1.873747	2.1429533	2.6474156
17.09402	2.44785	1.947438	2.2445195	2.7800367
17.70452	2.452474	2.059089	2.3401518	2.9226255
18.31502	2.441637	2.222942	2.4313013	3.0812093
18.92552	2.423784	2.441325	2.5228137	3.2525059
19.53602	2.407128	2.699856	2.6190635	3.4237586
20.14652	2.401588	2.96763	2.7205135	3.5779894

a

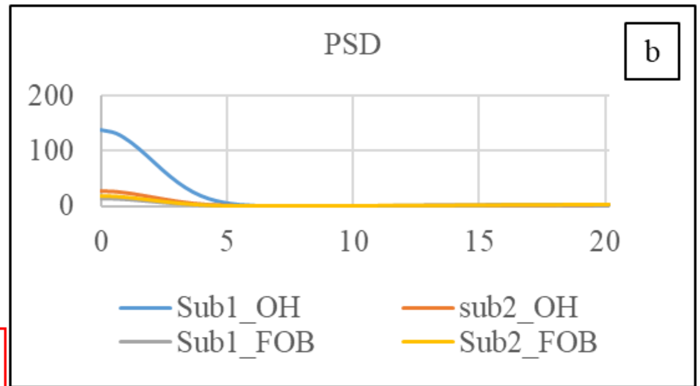

Figure 3.1 Illustration of the shaker PSD handle z-axis amplitude (m/s^2) under 20 Hz, including one example of actual shaker PSD values (a) and exemplary shaker PSD curves for two postures (b).

3.1.2 Accelerometer Adapter Base Validation

In the present study, the accelerometer was first attached to the subject skin directly using double-sided tape for the subjects 1, 2, and 3 during overhead testing. However, the subject 3 developed skin allergy possibly due to the combination of the double-sided tape and pressure (e.g., sharp edge of the accelerometers). The only location didn’t show allergy reaction was at the elbow where the sensor was attached to the skin with a rectangular 3D-printed plastic base and double-sided tape. Therefore, except the wrist accelerometer and the Exo accelerometer, circular 3D-printed plastic bases were used for the rest of 5 accelerometers for a better pressure distribution and avoidance of sharp edges for the subjects 1 and 2 in the remainder of the present study (i.e., the front-of-body test).

It is noteworthy that different models of accelerometers with varying dimensions were used in the present study for different locations with the elbow and the shoulder sensors in miniature forms and the rest sensors in normal sizes (Table 2.1). These accelerometers were superglued to the circular plastic bases and their frequency response was examined using the TIRA shaker system. Due to the limitation of the TIRA shaker in producing random vibration (i.e., white noise) with frequency below 8 Hz, the frequency range used for analysis was from 8 Hz to 1600 Hz.

Figure 3.2 shows the frequency responses of these accelerometer-base combinations with the PSD transmissibility varying from -0.7 dB to 2.4 dB for frequency range between 8 Hz and 1600 Hz. Figure 3.3 shows the same frequency response between 8 Hz and 500 Hz for a closer view. The range of the PSD transmissibility varied from -0.7 dB to 0.41 dB. The frequency response of the original setup of the elbow accelerometer with a rectangular base were also shown in Figure 3.2 and Figure 3.3, respectively, with PSD transmissibility comparable to PSD transmissibility with circular bases.

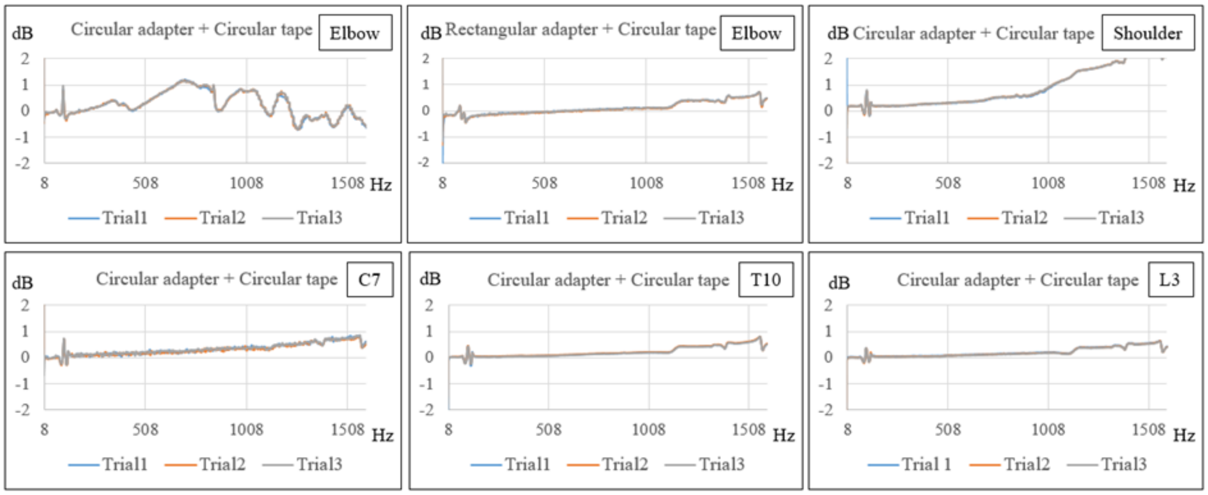

Figure 3.2 Accelerometer adaptor base frequency responses (dB) between 8 Hz and 1600 Hz

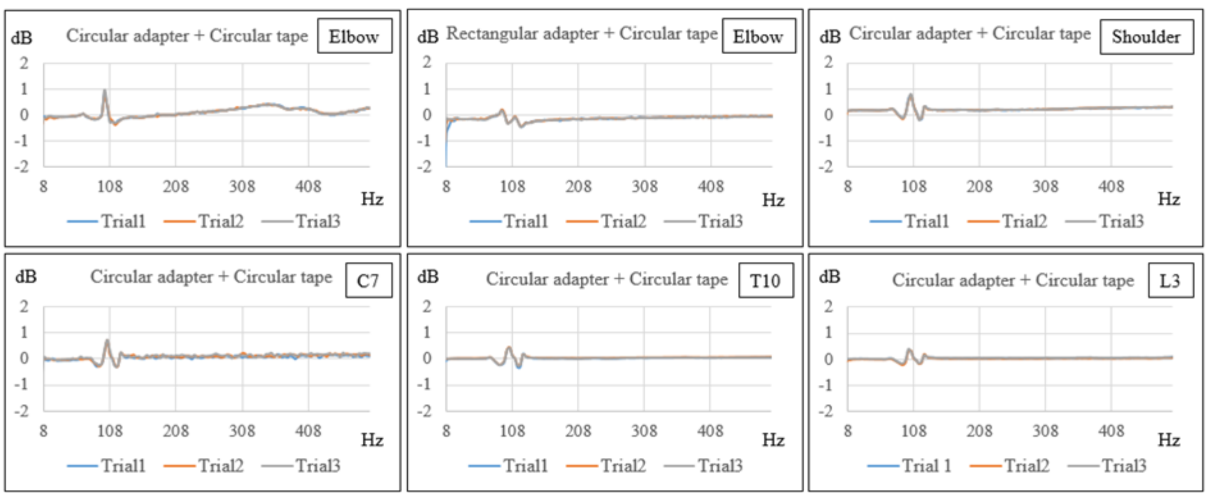

Figure 3.3 Accelerometer adaptor base frequency responses between 8 Hz and 500 Hz.

Figure 3.4 shows the frequency response of the wrist accelerometer-base combination from 8 Hz to 1600 Hz and a closer view between 8 Hz and 500 Hz. The PSD transmissibility ranged from -1 dB to 1 dB for the 8 Hz to 1600 Hz range and -1 dB to 0.5 dB for the 8 Hz to 500 Hz range, respectively.

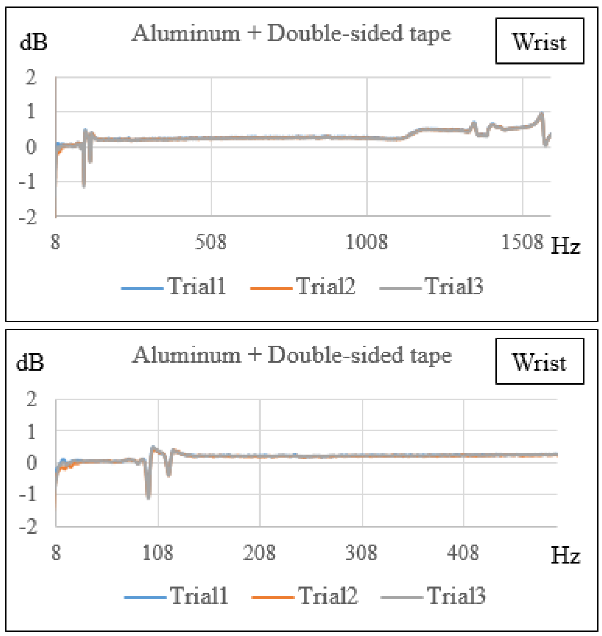

Figure 3.4 Wrist adaptor base frequency response of two frequency ranges from 8 Hz to 1600 Hz (up) and from 8 Hz to 500 Hz (down).

Figure 3.5 shows the frequency response of the Exo accelerometer from 8 Hz to 1600 Hz and a closer view between 8 Hz and 500 Hz using double-sided tape and wax as attachment methods. It is noteworthy that the wax attachment is the standard attachment method for acceleration assessment; in other words, the PSD transmissibility should be a perfectly flat line at

0 dB across the entire frequency range for wax attachment. The observations of a spike around 86 Hz to 128 Hz in the wax setup demonstrate that the spike observed for all other accelerometers is the intrinsic limitation of the TIRA shaker system instead of the issues of the plastic accelerometer adaptors and the wrist aluminum adaptor. Additionally, there was increased PSD transmissibility above 1200 Hz that was observed for other accelerometers too, indicating another limitation of the TIRA shaker system. It is also noteworthy that while the TIRA shaker system can’t be used to validate the frequency response below 8 Hz, the reliability of the plastic bases at such low frequency shouldn’t be a concern since the bases is made of a solid material. Additionally, the shaker is only reliable in producing random vibration above 7 Hz as shown in section 3.1.1. It is reasonable to assume the circular plastic accelerometer adaptors are proper for assessing vibration above 7 Hz.

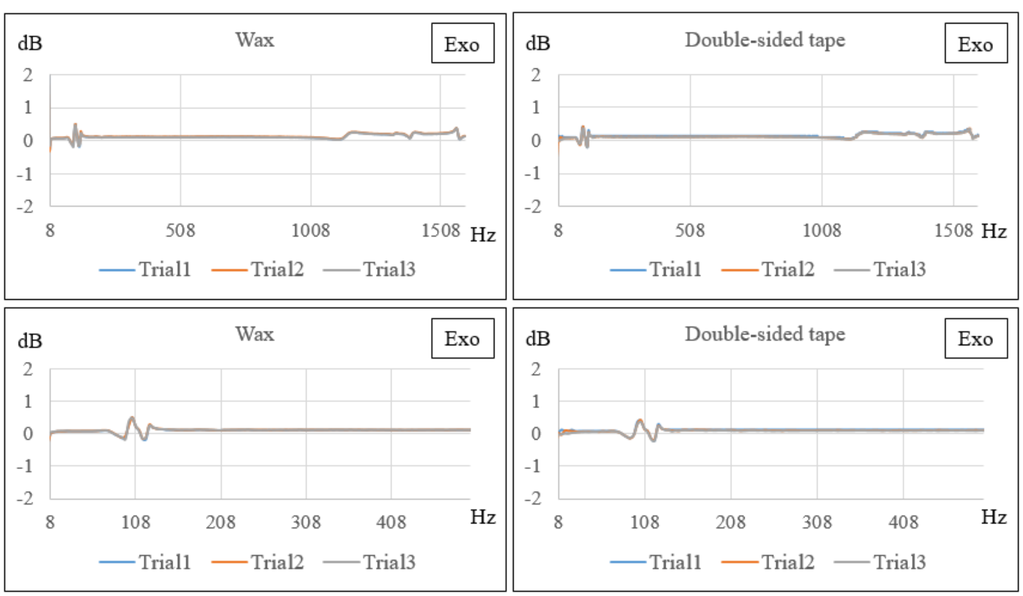

Figure 3.5 Bare accelerometer frequency response at the Exo arm link with two attachment methods for frequency ranges from 8 Hz to 1600 Hz (up) and from 8 Hz to 500 Hz (down).

3.1.3 Maximum Voluntary Contraction (MVC) Testing Protocol

In the present study, a high-throughput MVC testing protocol was adopted to allow the testing of nine shoulder muscles in just 2 minutes. However, there were cases that the maximum EMG activity occurred at tests of different muscles. For example, Figure 3.6.a illustrates that the maximum activity of the anterior deltoid was detected in the first time interval as expected (marked with a circle and a star overlapping each other). However, Figure 3.6.b shows that the maximum activity of the latissimus dorsi was detected in the third time interval (marked with a star) instead of the expected fourth time interval (marked with a circle). These observations suggest that this MVC testing protocol may not always trigger max response as intended and more testing is needed to validate the protocol.

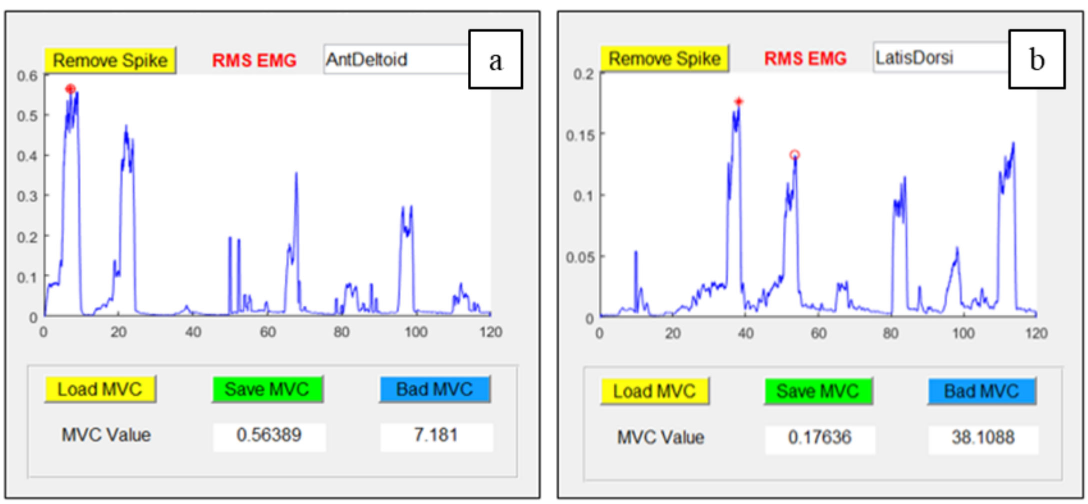

Figure 3.6 Examples of MVC data in RMS with the maximum value occurred at the expected time interval (a: overlapping circle and star markers) and maximum value occurred at the unexpected time interval (b: the circle and the star markers not overlapping each other).

3.1.4 Determination of Frequency Range for Vibration Transmissibility Calculation

The sections 3.1.1 helps to determine the lower range of the frequency range for VT calculation at 7.3 Hz due to the limitations of the shaker system and the way the PSD was calculated in MATLAB with the sampling frequency at 5 KHz. The upper limit at 500 Hz was determined in part in the section 3.1.2 to achieve a flat response curve with variability in a tight range such as within ±1 dB. Additional evidence of the choice of the upper limit at 500 Hz can be found in the section 3.2.2 where the PSD transmissibility in the frequency domain is presented. Essentially, the maximum transmissibility above 500 Hz was so low (below 0.0001 in PSD transmissibility or 0.01 in RMS transmissibility) that any frequency content above 500 Hz can be ignored.

3.2 Pilot Human Subject Testing Results

In the present study, 3 right-handed male subjects were enrolled. Subject 3 showed allergic reaction to the accelerometer assessment procedures during the overhead testing. His data were not used in the pilot results presented here. Subjects 1 and 2 completed both the overhead testing protocol and the front-of-body testing protocol and their data were processed and analyzed. Descriptive results in mean and standard deviation (SD) are presented in the sequence of the 3 main factors (i.e., posture, exoskeleton, and vibration conditions) wherever proper. No interaction effect between the main factors was analyzed due to the small sample size at 2.

3.2.1 Vibration Level Along The Right Arm And The Spine

3.2.1.1 Posture Effect

In the present study the acceleration amplitude was computed directly using raw acceleration data in the time domain without any treatment. Figure 3.7 shows vibration magnitude (Acc3D) at the shaker handle, wrist, elbow, shoulder, C7, T10 and L3 for two testing postures. The acceleration level decreased drastically along the arm and the spine from 14 m/s^2 at the wrist to 0.2 m/s^2 at the lower back based on the distance of the body parts from the shaker handle (78 m/s^2). The Exo acceleration level was between the elbow and the shoulder values as the Exo accelerometer was placed at the arm link, thus closely representing the vibration of the upper arm. The second observation is either lack of or small difference in acceleration level between two postures. Given that the overall vibration level was quite low at the shoulder when compared to the shaker handle, the small difference between two postures may not be significant in terms of health effect due to transmitted vibration. Even less is concerned for the middle back and the lower back. The third observation is the low SD values compared to the mean values of from 2 subjects and 3 Exo conditions, indicating that the propagation of vibration along the human body may not be much different from individual to individual or wearing Exos.

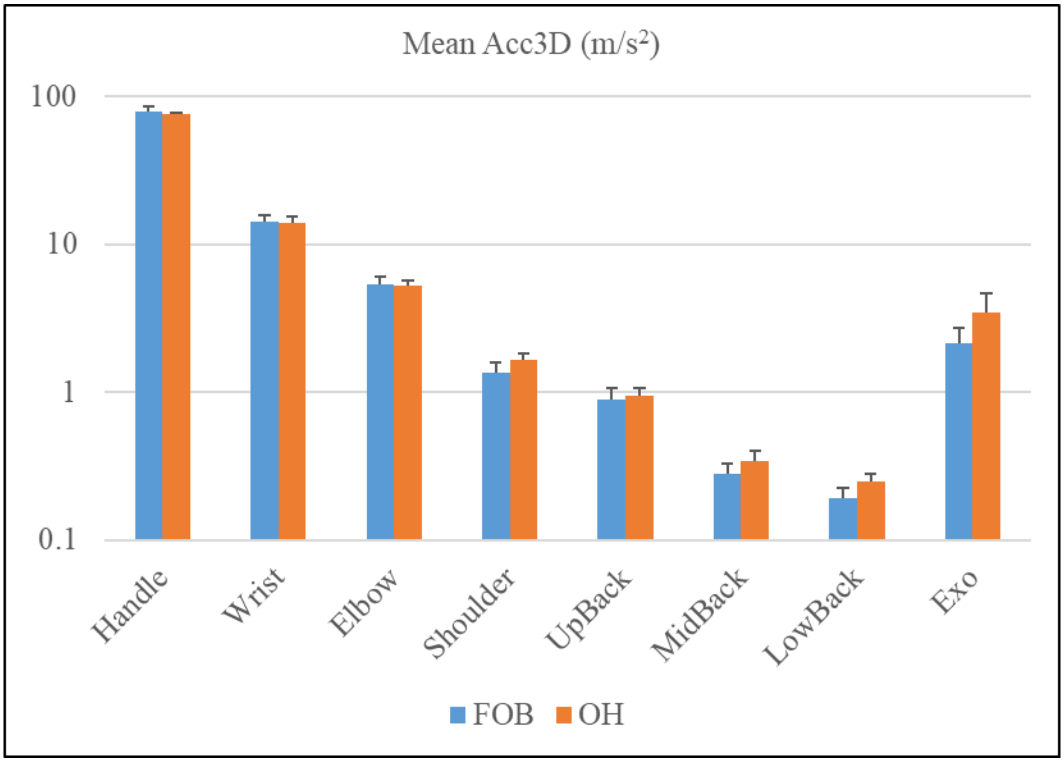

Figure 3.7 Posture effect on mean acceleration magnitude at the shaker handle, six body locations, and the exoskeleton. OH: overhead posture; FOB: front-of-body posture.

3.2.1.2 Exoskeleton Effect

Figure 3.8 shows vibration magnitude at the shaker handle, wrist, elbow, shoulder, C7, T10 and L3 for three Exo conditions. Same as the observations from the posture effect, the vibration level decreased drastically along the arm and the spine based on the distance of the body parts to the shaker handle. While the acceleration at the shoulder, middle back and lower was slightly higher under the Vest Exo condition, the low vibration amplitude compared to the vibration at the shaker handle indicates the effect may not be significant. Again, the acceleration level at the Exo was between the values from the elbow and the shoulder.

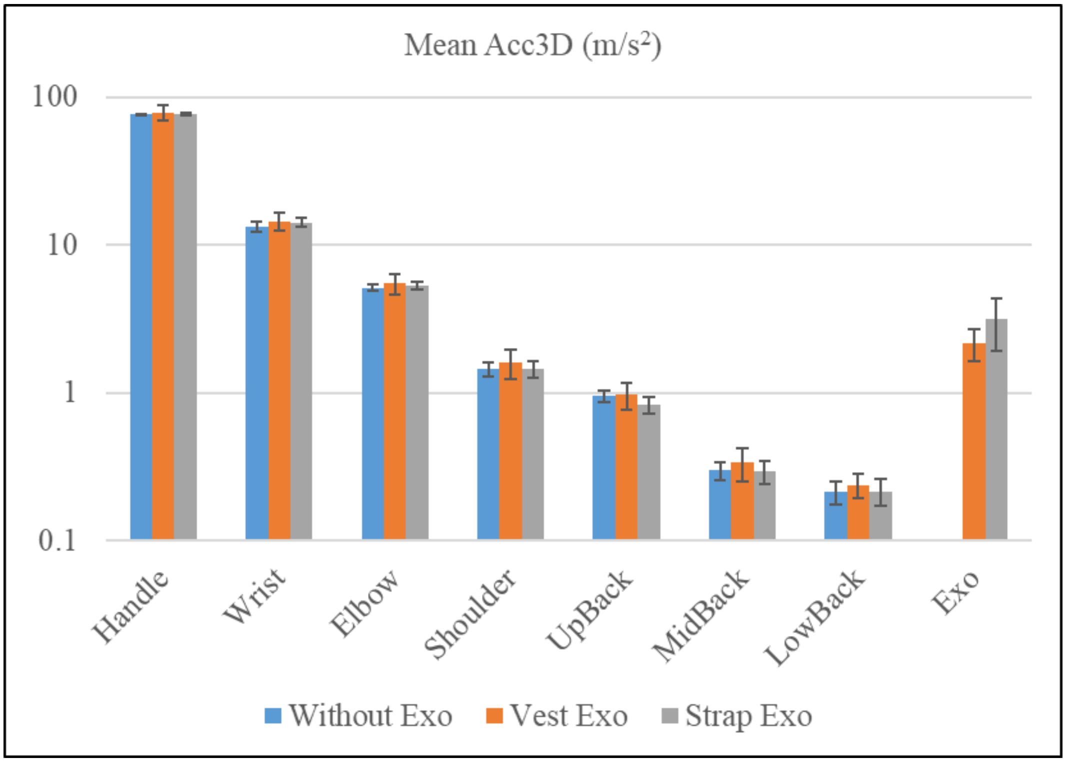

Figure 3.8 Exoskeleton (Exo) effect on mean acceleration magnitude at the shaker handle, six body locations, and the arm link of exoskeletons.

3.2.2 Vibration Transmissibility Along The Right Arm And The Spine

Transmissibility for the random vibration in the present study (PSD transmissibility) was calculated as the ratio of area under the curve of PSD between two locations for the frequency range between 7.3 Hz and 500 Hz. It is noteworthy that the amplitude of PSD transmissibility is the RMS transmissibility amplitude squared (e.g., a PSD transmissibility at 100 is equal to a RMS transmissibility at 10). PSD was calculated using the pspectrum function in MATLAB. The PSD transmissibility was computed with the shaker handle acceleration as input location and the rest of acceleration assessment locations as output. It is noteworthy that the PSD transmissibility data are recommended for random vibration analysis. Additionally, PSD transmissibility data were computed in the right frequency range while the direct acceleration data were not (see section 3.2.1). Nevertheless, the observations are similar from these two datasets in term of understanding vibration transmitted along the body.

3.2.2.1 Posture Effect

Figure 3.9 shows the effect of posture on the VT along the arm and the spine. Similar to the observations of the acceleration level at different locations, the PSD transmissibility decreased drastically based on the distance of the body parts to the shaker handle. The overhead posture led to a slightly increased VT starting from the shoulder to the lower back, although there was no effect on the trend of the VT amplitude at different body locations. In other words, given the small VT values, the associated health effect may not be significant. Also similar to the acceleration data, the SDs of the data were small compared to the means, indicating the effects of individual factors and wearing Exo may not be significant.

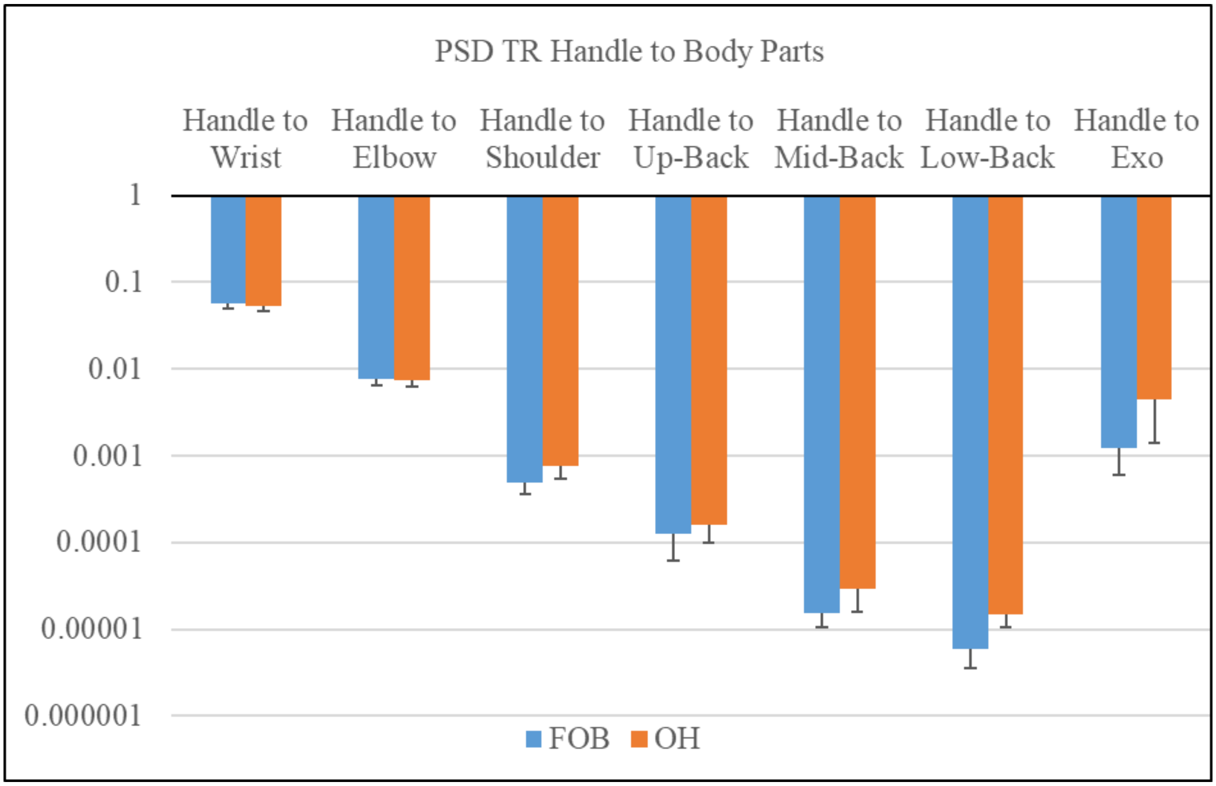

Figure 3.9 Posture effect on PSD transmissibility. OH: overhead posture; FOB: front-of-body posture.

3.2.2.2 Exoskeleton Effect

Figure 3.10 shows PSD transmissibility along the body under different Exo conditions. Same as the observations from the posture effect, VT decreased drastically along the arm and the spine based on the distance of the body parts to the shaker handle. There was no clear effect observed for VT under different Exo conditions.

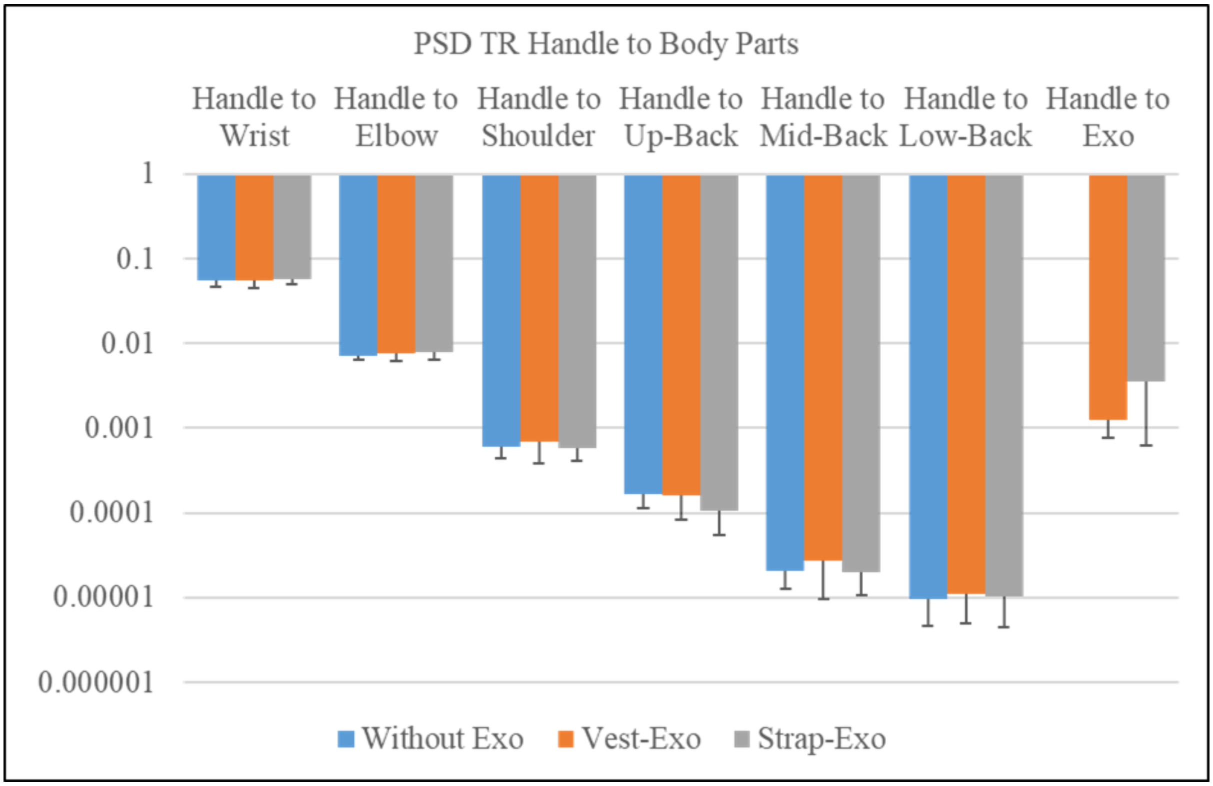

Figure 3.10 Exoskeleton (Exo) effect on PSD transmissibility

3.2.2.3 Transmissibility in The Frequency Domain

The sections 3.2.2.1 and 3.2.2.2 provide the results for overall VT. VT can also be examined in the frequency domain to obtain very useful information such as resonance behavior, amplification zone, and isolation zone of vibration systems. Observations made in the frequency domain also provide useful information related to data treatment such as frequency range of interest and data processing parameters (e.g., for filters) (Figure 3.11 and Figure 3.12).

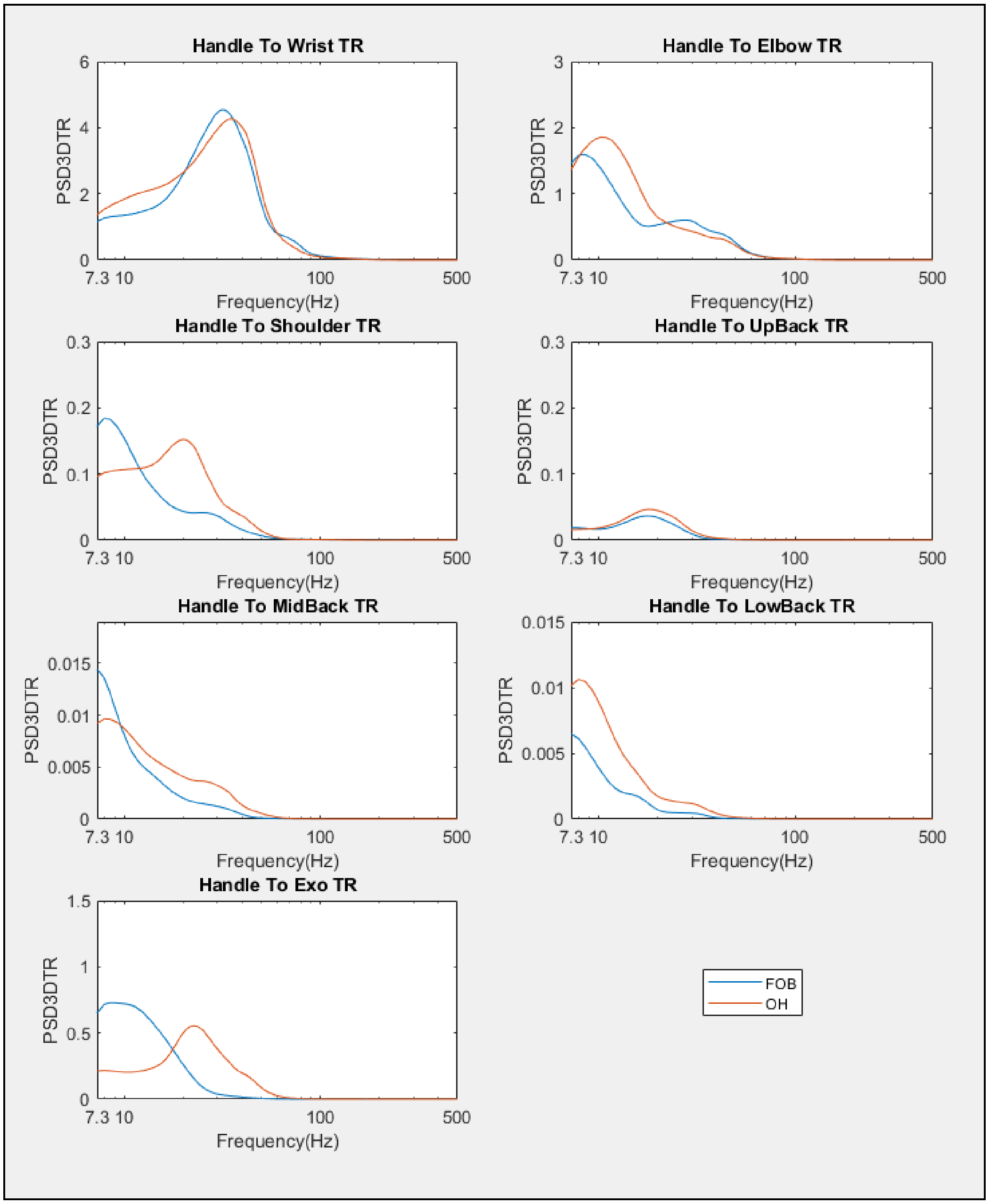

Figure 3.11 Posture effect on PSD transmissibility in the frequency domain. OH: overhead posture; FOB: front-of-body posture.

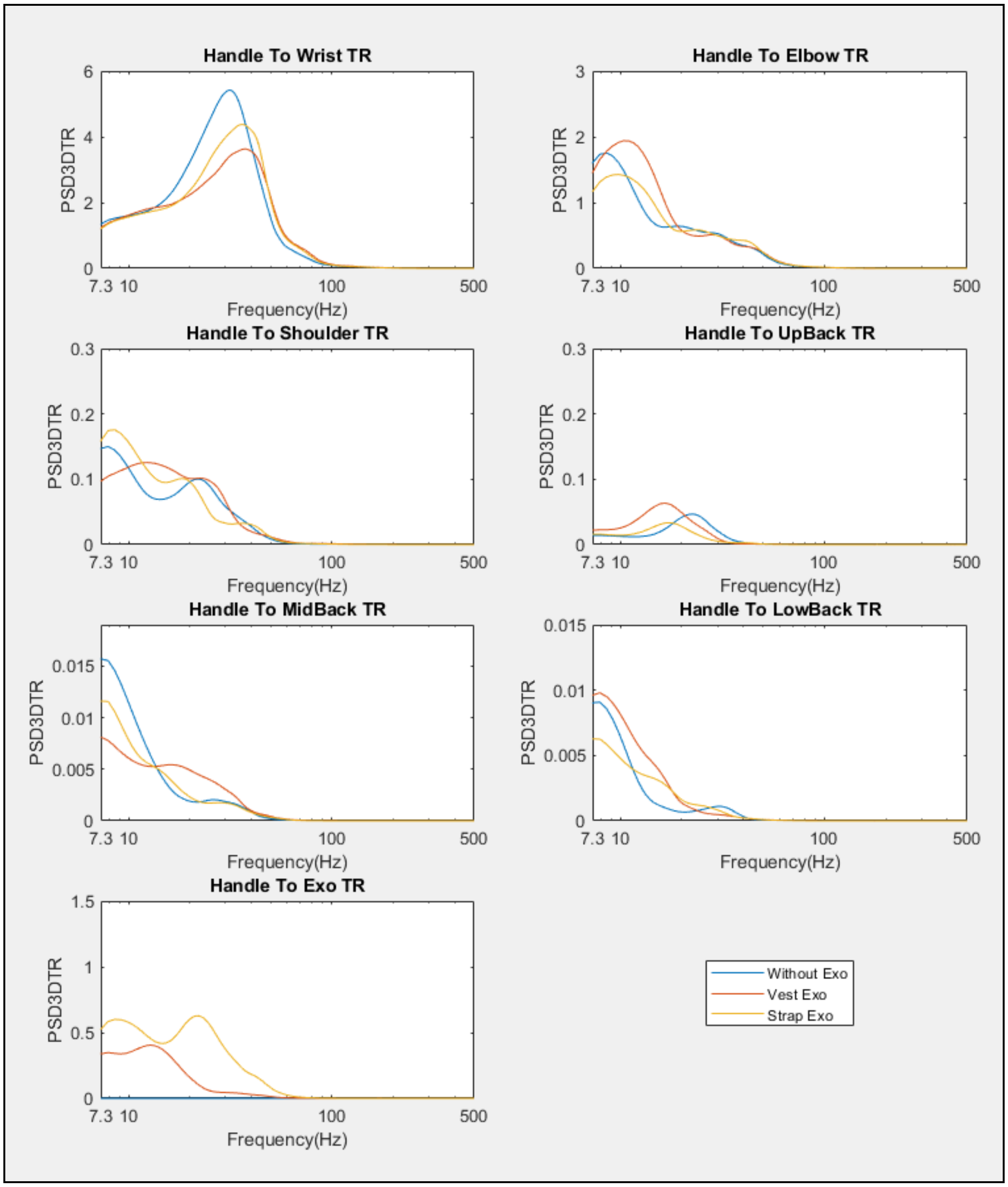

Figure 3.12 Exoskeleton (Exo) effect on PSD transmissibility in the frequency domain.

Figure 3.11 and Figure 3.12 show the effects of posture and Exo conditions on PSD transmissibility. Compared to the front-of-body posture, the overhead posture resulted in a significant shift of peak transmissibility from 8 Hz and 25 Hz at the shoulder. The frequencies for the peak transmissibility were 30 Hz and 40 Hz at the wrist, 8 Hz and 11 Hz at the elbow, 18 Hz and 25 Hz at C7, and 7 Hz and 9 Hz at T10 and L3 with a tendency of shift to a slightly higher frequency in the overhead posture. The peak transmissibility magnitudes were 4 to 4.5 at the wrist, 1.5 to 2 at the elbow, 0.15 to 0.2 at the shoulder, 0.05 at C7, 0.009 to 0.015 at T10, and 0.006 to 0.01 at L3. These results demonstrate that peak VT decreased significantly along the arm, although the peak values were similar for the shoulder, C7, T10, and L3. When grouped according to the Exo conditions, the peak frequencies for VT were similar at each body locations. The peak VT values were varying according to Exo conditions. The most pronounced location is the wrist where wearing Exos led to a decrease in peak VT value from 5.8 to 3.5. The peak VT amplitude were roughly similar at other body locations. Overall, vibration amplification (VT > 1) was observed at the wrist and the elbow, while vibration isolation (VT < 1) was observed for the rest of body locations and the Exo's arm link.

3.2.3 Muscle Activity

Descriptive data are presented to demonstrate the effects of posture, exoskeleton, and vibration conditions on both the raw mean RMS EMG and normalized mean RMS EMG for nine shoulder muscles examined in the present study.

3.2.3.1 Posture Effect

Figure 3.13 and Figure 3.14 show raw EMG and normalized EMG data under two postures, respectively. Except for the pectoralis major and the biceps, the shoulder muscle activities were significantly higher in the overhead posture, especially for the anterior deltoid and upper trapezius, which are considered the main agonist muscles in the overhead work.

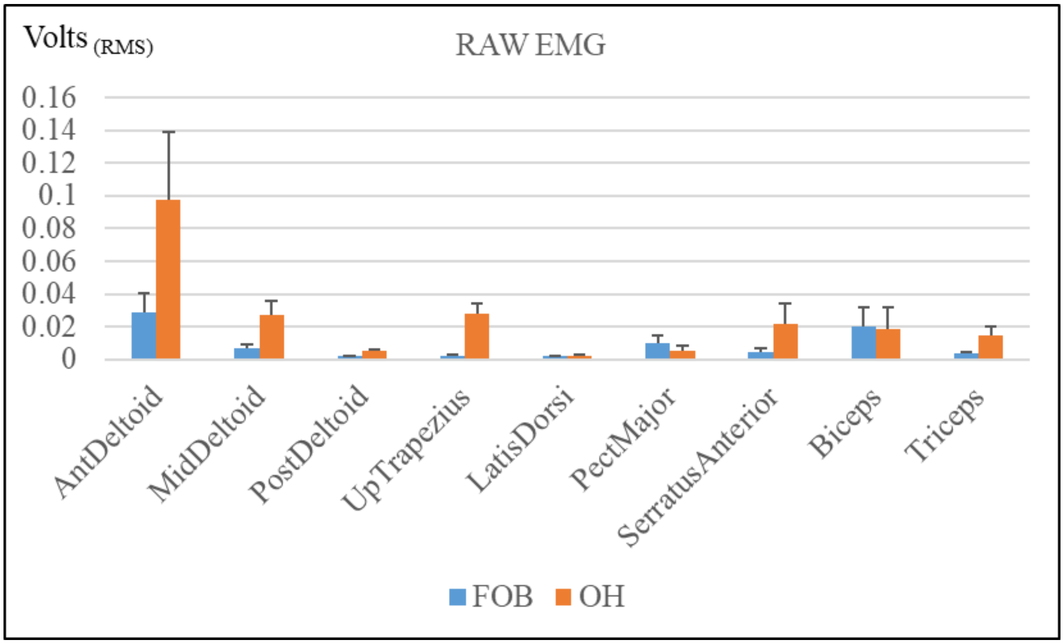

Figure 3.13 Posture effect on raw EMG (Volts in RMS) for 9 muscles. OH: overhead posture; FOB: front-of-body posture.

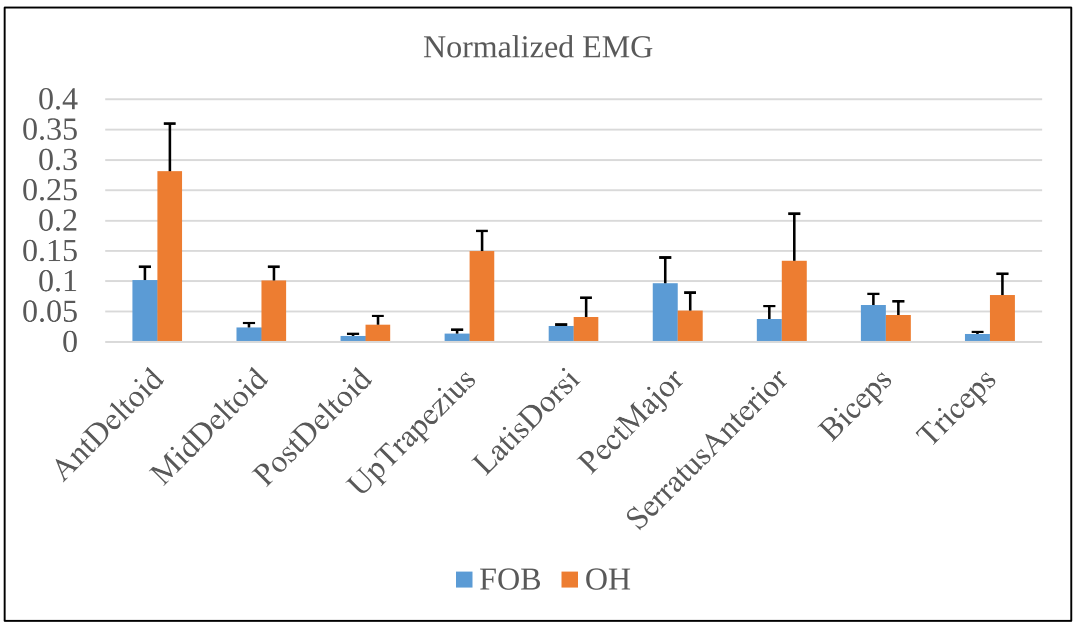

Figure 3.14 Posture effect of on normalized EMG for 9 muscles. OH: overhead posture; FOB: front-of-body posture.

3.2.3.2 Exoskeleton Effect

Figure 3.15 and Figure 3.16 show raw EMG and normalized EMG data under three Exo conditions, respectively. Most muscles examined exhibited lower activities with Exos.

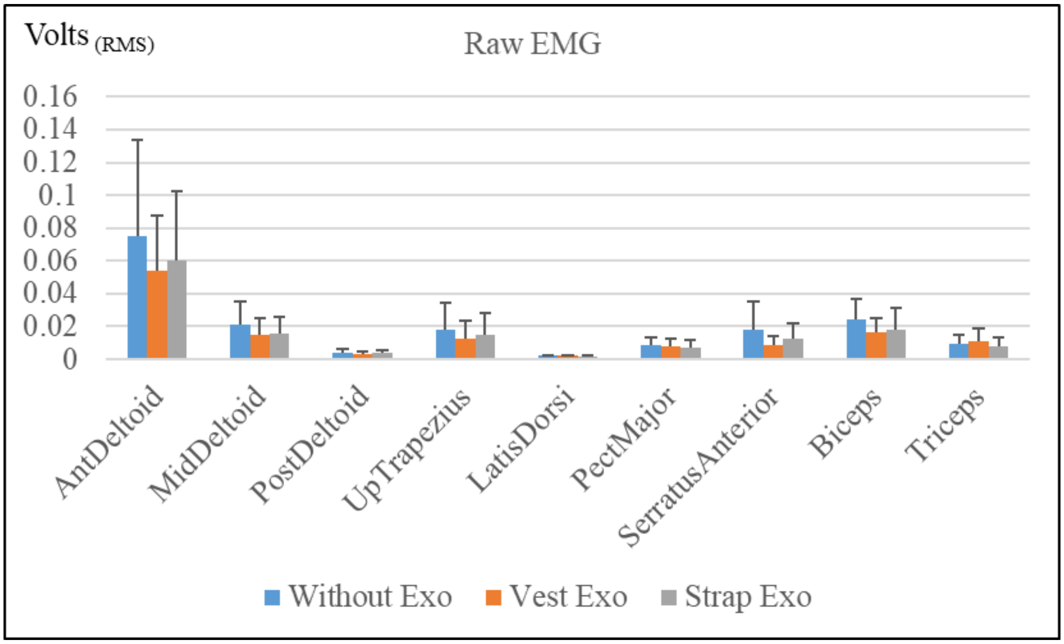

Figure 3.15 Exoskeleton (Exo) effect on Raw EMG for 9 muscles.

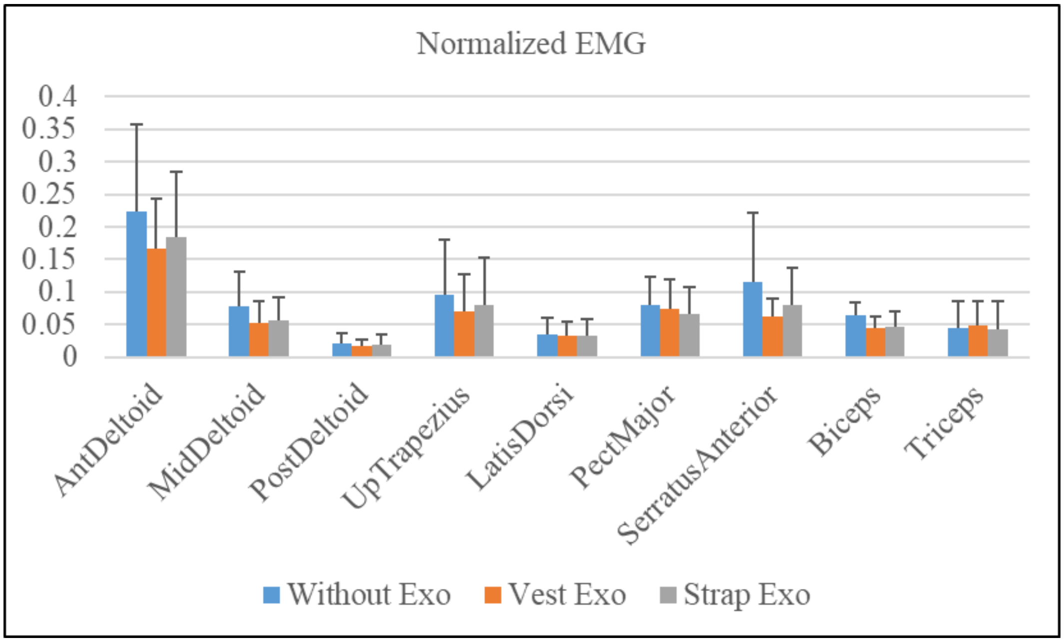

Figure 3.16 Exoskeleton (Exo) effect on normalized EMG for 9 muscles.

3.2.3.3 Vibration Effect

Figure 3.17 and Figure 3.18 show raw EMG and normalized EMG data under two vibration conditions, respectively. Muscle activities appeared slightly higher for upper trapezius, pectoralis major, biceps, and triceps when the vibration was turned on. Because random vibration was used in testing, it may be hard to remove motion artifact contamination, if any, from the EMG data. Nevertheless, given the small difference in the muscle activities even at the upper arm, in addition to the VT peak below 20 Hz that can be at least partly removed by the EMG hardware (i.e., band-pass between 25 and 450 Hz), the effect of vibration on shoulder EMG data may not be significant. However, it doesn’t mean the EMG data collected at the hand and forearm are free from vibration-induced motion artifact.

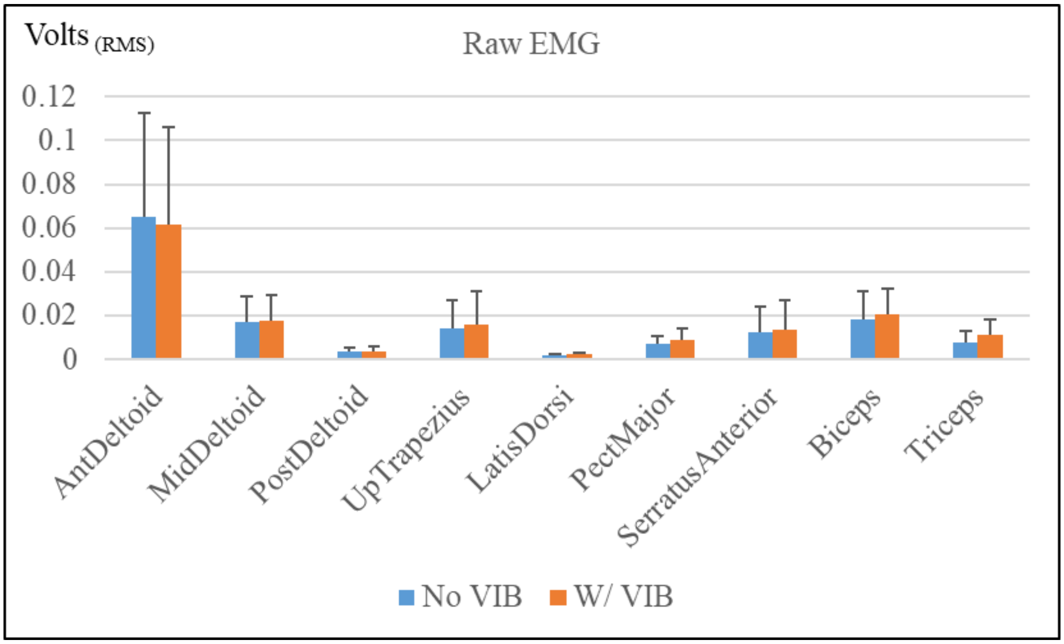

Figure 3.17 Effect vibration on/off conditions on Raw EMG for 9 muscles.

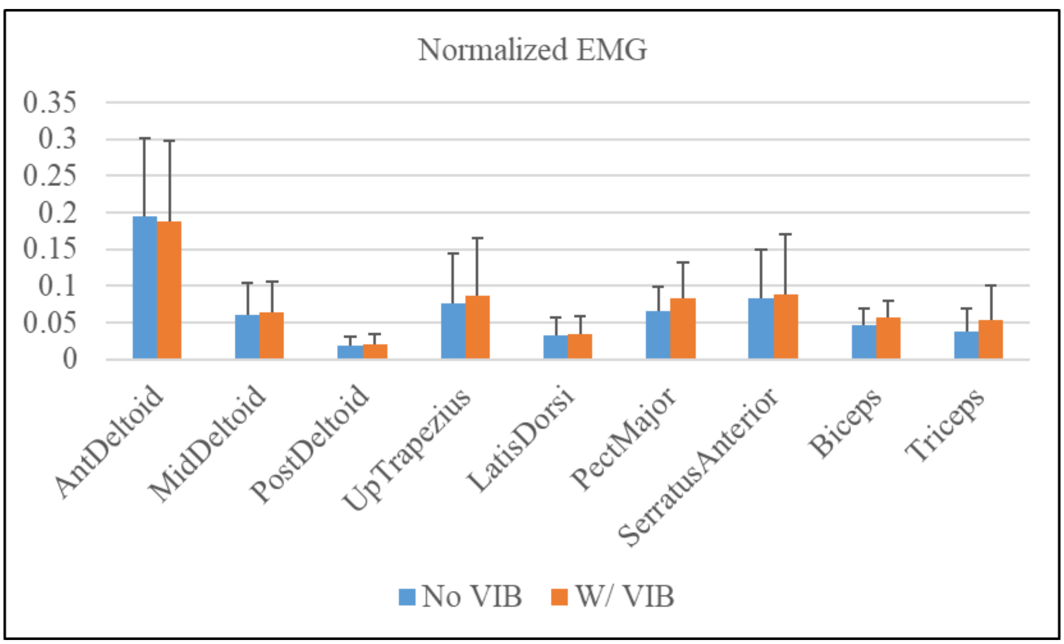

Figure 3.18 Effect of vibration on/off conditions on normalized EMG for 9 muscles

3.2.4 Coupling Forces

In the present study, the coupling forces as represented by grip force and push force on the shaker handle were examined. The mean coupling forces were controlled by subject under live feedback. As expected, the mean grip force and push force were close to 30 N and 50 N under different posture (Figure 3.19), Exo (Figure 3.20), and vibration conditions (Figure 3.21).

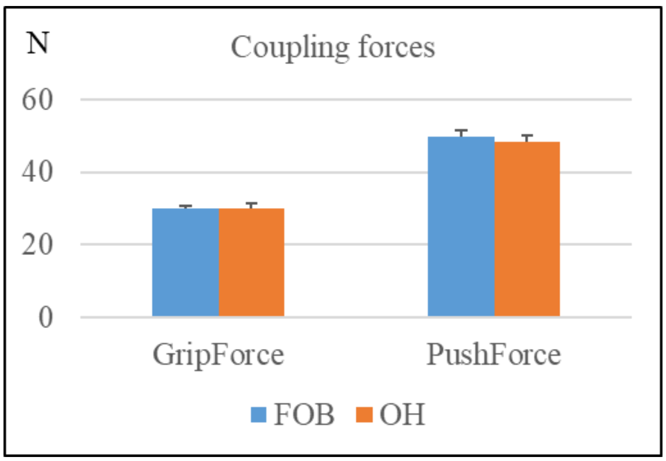

Figure 3.19 Posture effect on mean coupling forces. OH: overhead posture; FOB: front-of-body posture.

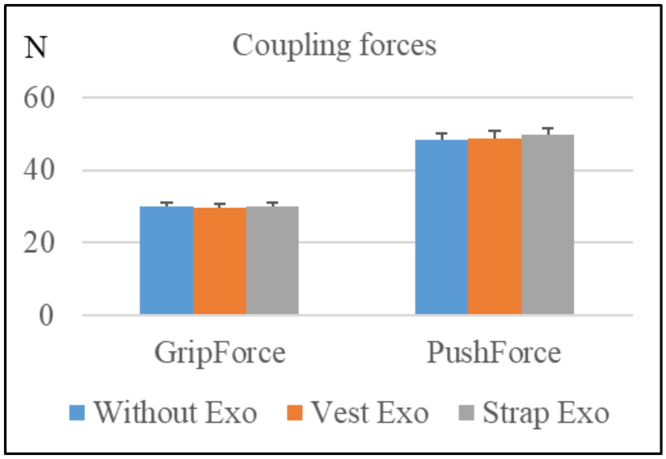

Figure 3.20 Exoskeleton (Exo) effect on mean coupling forces.

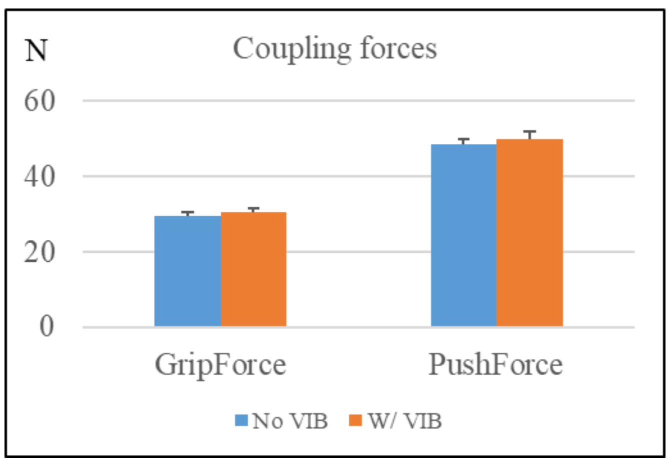

Figure 3.21 Effect of vibration on/off conditions on mean coupling forces

On the other hand, the SD of coupling force represents the peak-to-peak change of force amplitude within a single trial. It can be used to demonstrate the effectiveness of the subjects controlling grip and push activities. It can also be used to interpret the peak mechanical load the shaker handle acting on the body. The peak push force is perhaps more interesting as it has to travel through the entire body (from the hand to the foot) to be detected by the force plate placed under subject's feet. High fluctuation in the push force indicates significant mechanical load on the body. On the other hand, the grip force more likely represents coupling between the hand-arm system with the shaker handle instead of mechanical load exerted on the body parts far away from the handle.

3.2.4.1 Posture Effect

Figure 3.22 shows the SD of coupling forces under two posture conditions. There was a moderately higher peak push force for the overhead posture, indicating the body experienced a higher mechanical load in the overhead posture.

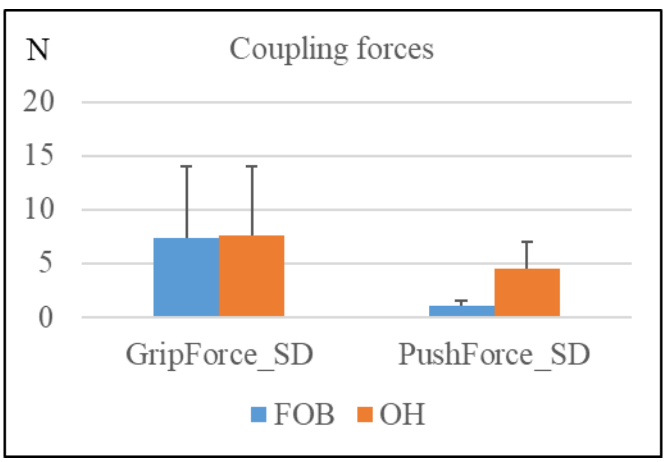

Figure 3.22 Posture effect on peak-to-peak coupling forces. OH: overhead posture; FOB: front-of-body posture.

3.2.4.2 Exoskeleton Effect

Figure 3.23 shows the SD of coupling forces under three Exo conditions. No effect of Exo condition on coupling forces was observed.

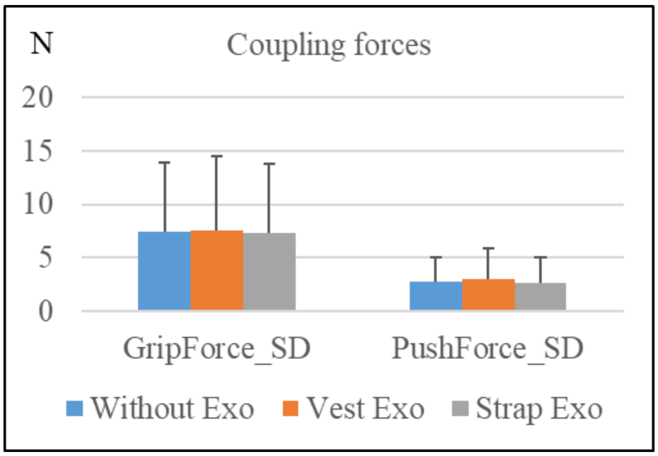

Figure 3.23 Exoskeleton (Exo) effect on peak-to-peak coupling forces.

3.2.4.3 Vibration Effect

Figure 3.24 shows the SD of coupling forces under two vibration conditions. There were a significantly higher peak grip force and a moderately higher peak push force observed with vibration turned on. These observations are obvious, especially for the grip force. The higher peak push force indicates the vibration can increase mechanical load in body part away from the shaker handle.

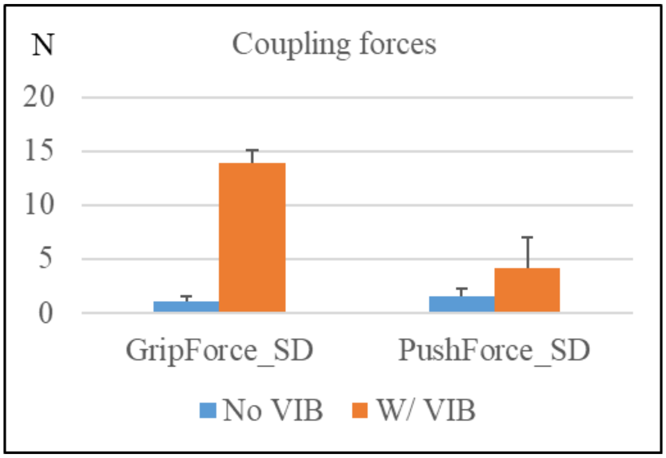

Figure 3.24 Effect of vibration on/off conditions on peak-to-peak coupling forces.

CHAPTER 4: DISCUSSION

4.1 Major Outcomes of The Present Study

Given the prevalent adverse effect of overhead postures such as shoulder injuries and a rising interest of using occupational exoskeletons in the workplace especially in manufacturing and construction industries involving overhead tasks with power hand tools, this thesis research aimed to create a comprehensive study protocol to assess the combined effects of overhead posture and exoskeleton on vibration transmitted to the hand-arm structure and the spine and shoulder muscle activities. In the present study, an electrodynamic shaker system was used to create an extended random vibration spectrum from 3 Hz and 1600 Hz adapted from the ISO 10819 (2013). The VT along the arm and the spine was assessed using triaxial accelerometers placed at the wrist, elbow, shoulder acromion, C7, T10 and L3 spinous processes. Activities of 9 muscle groups surrounding the right shoulder were assessed using surface EMG. Further, the coupling forces between the subjects and the shaker system were assessed using the standard procedure described in the ISO 10819 (2013), particularly the grip force at the shaker handle and the push force at the subject's feet.

A full-factorial, nested study design was employed with posture (overhead and front-of-body), Exo (no Exo, vest-type Exo, and strap-type Exo) and vibration (on and off) conditions as level 1, 2, and 3, respectively. Three right-handed male subjects were recruited in the study to validate the study protocol and to provide pilot data for future studies. Spectral analysis of the shaker vibration data suggest that the shaker system can deliver random vibration more reliability above 7 Hz. Additionally, the PSD analysis of VT along the body suggest that 7 Hz and 500 Hz is the proper frequency range for vibration analysis on human subjects. During the study, one subject developed skin reactions to the bare accelerometer placement protocol. This promoted the design of a circular accelerometer adaptor base to prevent excessive pressure over the skin and associated adverse effects. The frequency response of the circular adaptor bases was validated for random vibration assessment between 7 and 500 Hz. Finally, a high-throughput MVC protocol was developed to obtain MVC of 9 muscles in two minutes.

Descriptive results of human response collected from 2 subjects (the subject who developed allergy excluded) indicate that vibration amplitude and VT decreased drastically along the arm and the spine based on the distance of the body parts from the shaker handle. Posture and Exo conditions had little effect on VT along the arm and the spine. The shoulder muscle activities were more pronounced in the overhead posture, especially in the anterior deltoid and the upper trapezius, when compared to the front-of-body posture. Wearing Exos led to a smaller muscle activity in most muscles examined. 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 when compared to no vibration.

4.2 Overhead HAV Testing Setup

4.2.1 Source of Vibration Excitation and Waveforms

One uniqueness of the present study is the ability to study the effects of HAV in the overhead posture using an electromagnetic shaker suspended upside-down from the roof. The only other study found in the literature that used the similar overhead setup was by Rohmert et al. (1989). The equipment used in the Rohmert et al.'s study was a compact B&K 4808 shaker with force ratings up to 187 N. The experience of using the TIRA TV 51120 shaker system with a peak force rating at 200 N in the present study revealed that these compact shaker systems are not capable of delivering random vibration defined in ISO 10819 (2013), thus not proper for standard HAV testing using random vibration excitations. The LDS V651 system used in the present study has force ratings up to 2.2 KN. It is fully capable of delivering the random vibration defined in ISO 10819 (2013). In fact, the system can push the envelope to as low as 7 Hz for random vibration excitations as demonstrated by the present study. It is noteworthy that shaker systems same or similar to the present study were commonly used for vibration testing in the front-of-body posture, which is the standard testing posture specified in HAV standards and guidelines such as ISO 5349-1 (2001) and ISO 10819 (2013) (Adewusi et al., 2010; Marchetti et al., 2017; Pan et al., 2018; Xu et al., 2017).

Alternatively, there were actual power hand tools used as the vibration source for overhead HAV testing, such as battery-powered drill (Maurice et al., 2020), impact wrench (Yin et al., 2020), and pneumatic drill (Kim et al., 2018), to name a few. The shaker system used in the present study is capable of simulating a variety of spectra including power hand tools, thus making it more versatile and more standardizable than actual tools. On the other hand, the requirement to suspend the shaker in the upside-down position can be challenging for many lab facilities without sufficient overhead space or proper roof structure. It is noteworthy that the shaker suspension system used in the present study can also allow orientation other than the vertical direction. More testing is needed to validate orientation setup in an oblique angle.

4.2.2 Frequency Range for Random Vibration Excitation and Transmissibility Analysis

Many HAV studies in the literature have used random vibration as excitation and reported corresponding vibration characteristics and vibration analysis parameters such as frequency range. Marchetti et al. (2017) assessed vibration transmitted to the elbow using random vibration between 6 Hz and 500 Hz and concluded that the frequency above 100 Hz was negligible for VT analysis. Pan et al. (2018) assessed VT at the wrist, forearm, and upper arm using a random vibration between 4 Hz and 500 Hz, as well as sinusoidal excitation at 10 Hz, 16 Hz, 25 Hz, and 40 Hz. They found that the human arm resonances mostly happened in the range of 10 Hz and 40 Hz. They suggested that the frequency range for VT analysis below 100 Hz was sufficient. Adewusi et al. (2010) studied response to random vibration between 2.5 Hz and 2500 Hz and analyzed vibration data between 2.5 Hz and 500 Hz. Xu et al. (2017) measured VT along the upper body using random vibration between 4 Hz and 100 Hz and analyzed the data using the same range. According to ISO 10819 (2013), the random excitation range is set between 25 Hz and 1600 Hz in one-third octave bands. According to ISO 5349-1 (2001), the one-third octave bands between 8 Hz and 1000 Hz can be used to assess vibration injuries because no substantial vibration energy exists for frequency bands at or below 6.3 Hz.

The PSD frequency range used in the present study is consistent with the ISO 5349-1 (2001) and the literature. In the present study, the random vibration used had a frequency range between 3 Hz and 1600 Hz, although the PSD analysis reveals that the shaker system could only function properly from 7 Hz and up for random vibration excitations. For VT analysis in the present study, the frequency range was used between 7.3 Hz and 500 Hz. The particular lower limit value at 7.3 Hz was an artificial effect of the PSD procedure and the sampling rate at 5000 Hz. It is noteworthy that the lower limit of the 8 Hz one-third octave band referred in the ISO 5349-1 (2001) is 7.1 Hz, which is very close to 7.3 Hz used in the present study. Nevertheless, an approximation to 7 Hz is used in writing this thesis when the number is referred in general. The human subject data collected in the present study also support the choice of frequency range. At 500 Hz, VT at the wrist was below 0.0001 in PSD transmissibility (or 0.01 in RMS transmissibility), indicating that any components above 500Hz can be ignored. Given that VT was lower for locations beyond the wrist, it is even a less concern for frequency above 500Hz at those locations.

4.3 Accelerometer Adaptor Base Validation

In the present study one subject developed allergic reactions to the direct attachment of bare accelerometers to the skin using double-sided tape. It was suspected that the high pressure created at the sharp edges of the accelerometers might cause the allergic response. Therefore, circular plastic adapter bases with a smooth edge were laser 3D-printed and superglued to the accelerometers for mounting of accelerometers to the skin for the remainder of the study. The frequency response testing demonstrated that these circular bases are proper for acceleration assessment on the skin with the range interested in the present study (i.e., 7 Hz and 500 Hz).

Vibration transmitted to the anatomic landmarks has been investigated in previous studies using a variety of adaptor bases as attachment methods. Kihlberg (1995) used small circular plastic bases for the finger at the size of 20 mm in diameter and for the wrist and elbow at the size of 25 mm as diameter (Kihlberg, 1995). Two types of excitations were generated using an electrodynamic shaker (B&K 4805) with one simulating impact hammers and one simulating grinders. The author suggested that the custom-built adaptor bases were suitable for assessing impact hammers with one-third octave bands between 20 Hz and 1000 Hz and suitable for assessing grinders with one-third octave bands between 60 Hz and 1000 Hz. Adewusi et al. (2010) used 4 triaxial accelerometers to obtain transmissibility at the wrist, two locations near to the elbow joint side of the forearm and the upper arm, and the upper part of the upper arm. The accelerometers were attached firmly to the body with aluminum plates and Velcro stripes to reduce skin artifacts (Adewusi et al., 2010). Random vibration between 2.5 Hz and 2500 Hz was used for testing. Pan et al. (2018) measured vibration at the wrist, mid forearm, and mid upper arm using the adaptors similar to the palm adaptor defined in ISO 10819 (2013) and elastic cloth bandage wraps (Pan et al., 2018). Random vibration between 4 Hz and 500 Hz, as well as sinusoidal excitation at 10 Hz, 16 Hz, 25 Hz, and 40 Hz, were used for testing. In Xu et al. (2017) study, vibrations transmitted to the upper arm, shoulder, neck, and head were obtained using laser vibrometer and 3 accelerometers with adapters made of magnesium, wood, and polylactic acid 3D printed and dimensions defined in the ISO 10819 (Xu et al., 2017). Elastic cloth bandage wraps were used to attached accelerometers on the skin. Random vibration with frequency range of 4 Hz and 100 Hz was produced using a shaker with dual handles. In the study by Kattle and Fernandez (1999), vibrations were generated by 12 rivet guns from 4 manufacturers (Kattle and Fernandez, 1999). Vibration transmitted to the hand, wrist, and forearm were obtained using triaxial accelerometers. These accelerometers were glued to a hand-held adapter as hand sensor, and glued to two bracelets for wrist and forearm. Aatola (1989) measured VT to the wrist using sweep sine from 10 Hz and 400 Hz created by a B&K 4813/4805 exciter (Aatola, 1989). An accelerometer (B&K 4371) was secured at the wrist (styloid process of ulna) using an acrylic base plate and a hose clamp. Cherian et al. (1996) measured VT to the hand, forearm, and upper arm using sinusoidal excitation in the frequency from 10 Hz and 200 Hz generated by an electrodynamic exciter (Cherian et al., 1996). Miniature accelerometers were placed at the middle finger using a ring adaptor, at the forearm using a bracelet, and at the upper arm using a lightweight aluminum strip with an elbow pad. Overall, while there have been many different types of adaptor bases used for acceleration attachment, these studies suggested a good frequency response between 4 to 500 Hz would be sufficient. In the present study, the lower end frequency reported was 8 Hz due to limitation that the TIRA shaker system was not capable of producing proper white noise vibration under 8 Hz. It is noteworthy that in theory the low frequency is not a particular concern for rigid solid materials. Therefore, the circular accelerometer adaptor bases were suited to study frequency between 7 and 500 Hz.

4.3.1 Locations of Accelerometer Placement

To prevent skin resiliency and other interferences on acceleration measurements, previous studies have suggested that accelerometers should be attached on or near to the bony areas on the skin to obtain accurate readings (Adewusi et al., 2010; Reynolds & Angevine 1977; Wasserman, 1987). In the present study, the accelerometers were placed at the following locations: between the radial and ulnar styloid processes at the wrist, the elbow lateral epicondyle, shoulder acromion, and C7, T10, and L3 spinous processes. These placement locations are consistent with the recommendation and previous studies.

In studies examining VT along the arm, vibration transmitted to the wrist was obtained at styloid process of ulna (Aatola, 1989; Pyykkö et al., 1976; Reynolds & Angevine, 1977). Vibration transmitted to the elbow was assessed at the medial or lateral epicondyle and olecranon of the elbow (Pyykkö et al. 1976; Reynolds & Angevine 1977). Vibration transmitted to the shoulder was assessed at the shoulder acromion (Adewusi et al. 2010; McDowell et al. 2019; Reynolds & Angevine 1977).

For vibration transmitted to the spine, most previous studies were done under whole-body vibration. Tankisheva et al. (2013) assessed vibration transmitted to the upper back at C7 spinous process during exposure to vertical sinusoidal whole-body vibration at 30Hz, 35Hz, 40Hz, 50Hz. Vibration transmitted to the thoracic vertebrae was assessed at T9 or T10 spinous process by Kiiski et al. (2008) and Matsumoto and Griffin (2000) during vertical whole-body vibration tests. Kiiski et al. (2008) and Matsumoto and Griffin (2000) also assessed vibration transmitted to the lower back at L3 spinous process.

4.4 Maximum Voluntary Contract Protocol

In this protocol study, a high-throughput MVC testing procedure was developed to obtain maximum EMG of 9 shoulder muscles. The entire procedure involves 8 movements that were performed in only 2 minutes. For MVC testing, dynamometers have been used for both static and dynamic strength assessment with programmable movements and are considered as the best technique available (Frey-Law et al., 2012; Law et al., 2010; Xia & Frey-Law, 2015). One major drawback of the dynamometer approach is it is very time consuming in setting up the experiments. Another major drawback is the high cost to obtain a dynamometer, thus not accessible for most researchers. Alternatively, movements against resistance applied either by testers or by varying apparatuses were often used though only suitable for isometric MVC testing. Also, the ability to elicit maximum joint torque and accuracy are arguable. Given the large number of muscles to test in the present study and no access to a dynamometer, the movement against resistance approach was a logical choice. It is noteworthy that it was not the intention of the present study to obtain the maximum force/moment values, but rather the maximum EMG activities associated with MVC movements.

Methods to elicit high EMG activities in the shoulder muscles have been reported in the previous studies (Al-Qaisi & Aghazadeh, 2015; Boettcher et al., 2008). For example, Al-Qaisi and Aghazadeh (2015) assessed maximum EMG in the anterior deltoid. The subjects were asked to flex the shoulder 90° in the sagittal plane and lift the elbow up against a strap placed at the distal end of the upper arm. The movement elicited a maximum EMG level 58% higher than the accepted MVC. In the present study, the same movement was adopted for testing anterior deltoid, though the resistance was applied by a tester instead of a strap. More or less modifications were made in the MVC movements for other muscles such that 9 muscles could be tested within 2 minutes without any equipment. Essentially, the subjects were asked to make MVC either against the resistance applied by a tester or against resistance created from agonist-antagonist cocontraction. While the high-throughput requirement was met, maximum EMG activities obtained using the present MVC protocol were not always consistent since in some tests the maximum EMG activities did not show up in the expected time interval. Therefore, the maximum EMG detected at any time interval was used for normalization in the present study, in part mitigated the inconsistency.

4.5 Pilot Outcomes

Regarding overhead HAV human subject outcomes, Rohmert et al. (1989) evaluated muscle activities in the overhead posture under sinusoidal vibration exposure at 30Hz using a compact B&K 4808 shaker. Kim et al. (2018), Maurice et al. (2020) and Yin et al. (2020) examined muscle activities, task performance, and physical demands when the subjects operated power hand tools in the overhead posture. Maciukiewicz et al. (2016) tested an overhead drilling task though the drilling tool was not turned on. In the present study, overhead random vibration effectively between 7 Hz and 1600 Hz was delivered using an electromagnetic shaker and VT along the right arm and the spine was assessed, in addition to muscle activities and coupling forces. To our knowledge the present study was the only one that assessed the VT and muscle activity extensively in overhead vibration exposure, while most previous studies focused primarily on muscle activities and subjective outcomes. Given few studies examined VT with overhead vibration tasks, the front-of-body vibration was tested in the present study for comparisons. Also, the present study makes a unique contribution to the literature by reporting the effects of wearing occupational exoskeletons on overhead HAV exposure. Since the data included are from 2 subjects only, the descriptive results are presented.

4.5.1 Vibration Transmissibility Along The Arm And The Spine

In the present study, the first observation made on human subject outcomes is the amplitude of the acceleration and 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 acceleration and transmissibility response with respect to distance from the shaker handle was also reported by previous studies (Adewusi et al., 2010; Pan et al., 2018; Xu et al., 2017). 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 (Xu et al. 2017). Except the neck, these values are similar to the ones reported for the front-of-body posture in the present study. Collectively, the peak VT frequencies of the hand-arm structure are in the range of 8 Hz and 40 Hz based on the literature and the present study. Vibration amplification at the wrist and elbow and vibration isolation at the rest of body locations have also been reported in the literature (Adewusi et al., 2010; Pan et al., 2018; Xu et al., 2017). It is noteworthy that these studies were done with the front-of-body posture. 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 Exo effect, there is a large body of literature examining performance of arm-supporting Exos in overhead tasks. However, few studies examined the overhead tasks with power hand tools and the use of exoskeletons simultaneously. This was the primary reason to conduct the present study. In the present study, the effects of two types of arm-supporting Exos were examined, including a Vest-type Exo (EksoVest) and a Strap-type Exo (Paexo). The condition of without wearing Exo was used as control. The major finding of the present study was that wearing Exo had minor effects on VT except at the wrist joint where the Peak VT values decreased significantly with Exos. Previously, McDowell et al. (2019) has measured accelerations in the front-of-body vibration with two Exos similar to Vest Exo and Strap Exo used in the present study (McDowell et al., 2019). The results that wearing Exo decreased vibration transmitted to the wrist are similar to the present study. McDowell et al., (2019) also reported similar peak VT frequencies compared to the present study (McDowell et al., 2019).

4.5.2 Muscle Activities

Increase in muscle activity at the upper trapezius in overhead tasks has been reported in previous studies. 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 (Kim et al., 2018). Maciukiewicz et al. (2016) studied forward drill tasks and found that the shoulder muscle activities were higher in the overhead posture than in the front-of-body posture, although the drill was powered off (Maciukiewicz et al., 2016). Regarding existence of vibration, increase in muscle activities was observed in the studies by Rohmert et al. (1989) and Kim et al. (2018) when vibration was enabled. 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. However, existence of vibration was not found to affect muscle activity much with only a slight increase in some muscles.

In the present study, there was a decrease in activity in most muscles examined. A larger sample size is needed to allow statistical testing of the difference. Reduction in shoulder muscle activity has been reported in the literature, particularly for the anterior deltoid in overhead drilling tasks (Kim et al., 2018; Maurice et al., 2020; Yin et al., 2020). Particularly, the exoskeleton used in the Kim et al., (2018) study was EksoVest, which is similar to the vest-type Exo used in the present study (Kim et al., 2018). Maurice et al. (2020) used a PAEXO Exo, which is similar to the strap-type Exo used in the present study (Maurice et al., 2020).

4.5.3 Coupling Forces

In the present study, coupling forces were controlled at 30 N for grip and 50 N for push force, which are the same as defined in the ISO 10819 (ISO 10819, 2013). The peak-to-peak coupling forces as calculated as SD over the 12 seconds of recording showed that overhead posture and 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. Vibration turned on also led to a significantly higher grip force, indicating higher mechanical load in the arm. There is no literature specifically looks at the peak-to-peak coupling force.

4.6 Limitations and Improvements To Be Made

There are a few limitations for the present study. First, only one accelerometer was attached at the right arm link of Exos since this location was closer to the shaker handle and potentially had the highest acceleration amplitude along the Exo frames. It would be ideal to also measure acceleration in other parts of the Exos to confirm this assumption. However, limited resources, including accelerometers, cables, conditioners and data acquisition board, were available to support this effort. On the other hand, given the low amplitude of vibration assessed at the upper, middle and lower back, the speculation of significant amount of vibration transmitted through the Exo structures to the trunk, at least for the Exos used in the present study, may not be a concern.

Second, data were collected for 12 seconds under each testing condition in the present study. The ISO 10819 (2013) specifies a recording time of 30 seconds minimum. However, both the mock tests conducted in the present study and the study by Rohmert et al. (1989) demonstrated that fatigue could build up quickly for overhead tasks and rendered the testing halted in the middle and invalid. Therefore, the testing time in the present study was set at 12 seconds and plenty of rest was allowed to prevent fatigue. A test of EMG median frequency can also be applied to identify fatigue in muscle activity (Mannion & Dolan, 1994; Bonato et al., 2001). While it is out of the scope of the present study to investigate the effectiveness of Exos in preventing fatigue from prolonged overhead tasks, it is definitely important to understand such effects.

Third, the random vibration excitation was verified to be valid only between 7 Hz and 1600 Hz for the LDS shaker system used in the present study. Since the frequency response of interest is at most between 4 Hz and 500 Hz, given the 4 Hz one-third octave band is between 3.57 Hz and 4.49 Hz and the 500 Hz one-third octave band is between 355 Hz and 710 Hz, the random vibration can be set between 3.57 Hz to 710 Hz and eliminate frequency content above 710 Hz. Doing so might allow the shaker system to have additional power to drive the lower end frequency. Alternatively, the amplitude of the random vibration excitation can be scaled down to a lower level such that the shaker could have the sufficient power to drive the lower end frequency. However, it will involve more testing to ensure the modified random excitation can elicit sufficient response from the subjects.

Fourth, the MVC testing protocol developed for the present study needs further improvement. There were cases that the maximum EMG value for a muscle was detected in the time interval designated for eliciting maximum activity in a different muscle, while in other cases the maximum EMG values were detected in the right interval for the same muscle. Such inconsistency suggest the movement may not always elicit MVC for the muscle. A potential method to improve the present MVC protocol is to compare it to the results generated using a dynamometer or to a less ideal condition compare it to resistance generated from strap or devices instead of tester.

Last but not least, the supporting torque generated by the Exos was set at the highest level in the present study. Testing at settings at a lower level or no torque may provide useful results.

CHAPTER 5: CONCLUSION

The primary aim of this thesis research was to create a study protocol to assess the combined effects of overhead posture and use of exoskeleton on human exposure to HAV. The study involved testing of the shaker setup, the accelerometer placement and signal analysis, a high-throughput MVC protocol development, and pilot human subject testing to verifying the study protocol. Spectral analysis of the shaker acceleration data suggest that the shaker system can deliver random vibration more reliability above 7 Hz. The circular plastic adaptor bases that were made for accelerometer placement on the skin without excessive pressure was validated for the frequency between 8 Hz and 500 Hz. The high-throughput MVC protocol allowed fast testing of 9 muscles in 2 minutes, though consistency was issue. Descriptive results of human subject testing indicate that the acceleration level and VT decreased drastically along the arm and the spine based on the distance of the body parts from the shaker handle. Posture and Exo 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 HAV 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.

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APPENDIX

EXPERIMENT PROCEDURES FOR HUMAN-SUBJECT TESTS

A.1 Approved Consent Form

Northern Illinois University
Consent to Participate in a Research Study

Title of Study: Hand-transmitted vibration in the upper extremity – a laboratory study on coupling effect and protective devices

Investigators

Name:	Ting Xia, PhD	**Dept:**	ME	**Phone:**	[redacted]
Name:	Donald Peterson, PhD	**Dept:**	ME	**Phone:**	[redacted]
Name:	Parisa Torkinejad Ziarati, BS	**Dept:**	ME	**Phone:**	[redacted]
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Name:	Tyler Vogen, BS	**Dept:**	ME	**Phone:**	[redacted]

Key Information
- This is a human subject research study involving hand-transmitted vibration under different coupling conditions (different levels of grip force and pushing force, wearing and not wearing anti-vibration gloves, wearing and not wearing occupational exoskeleton) and different working postures (front-of-body and overhead).
- The vibration you will experience is generated from an electromagnetic shaker (acting much like a subwoofer) that can simulate vibrations of commonly used power hand tools. You may also be asked to operate actual powered hand tools and perform simulated workplace tasks.
- Up to 20 healthy participants will be recruited for this study. There will be 2 study visits with each study visit lasting around 3 hours.
- The benefits include helping researchers like us to understand the effects of hand-transmitted vibration such that we can develop better protections for workers in need.
- The level of risks is no more than the potential risks encountered in a typical industrial site.

Description of the Study
The purpose of the study is to understand how vibration transmits along your hand, arm, and shoulder and how different operational conditions affect such vibration transmission.

We are inviting you to participate in this research study because you are a healthy adult who does not have a history of a major bodily injury or surgery, and not currently have any bodily pain or injury, and a hand size between 7 and 10. If you agree to participate in this study, you will be asked to do the following things (only checked boxes apply):

Upon arriving to the lab, you may want to change clothes if necessary. Please either wear or bring with you an outfit that allows you to expose your entire arm, shoulder and upper back easily, such as a loose t-shirt. In each test we will have you (the subject), 1 study coordinator to communicate with you (e.g., give instructions), and 1 computer/equipment operator at the same lab space the same time in order to complete the related study activities smoothly.

Vibration exposure
☐ The vibration-generating shaker will be placed either in front of you (front-of-body position) or hanging upside down over your head (overhead position). The shaker will generate either artificial vibration waveforms or waveforms mimicking power hand tool vibrations.

☐ You will grab and/or push against the shaker (or tool) handle with different level of efforts according to the instructions. You will watch at a computer monitor showing your live grip and push forces and try to maintain the levels of forces within the target range. The level of force you will generate is no more than 20 lbs.

☐ We will use rubber band or other apparatus to generate pressure over your hand to simulate grip force when you are exposed to the vibration generated from the shaker. You will either fully relax your hand or maintain a lower level of grip force as instructed.

☐ We will ask you to wear special gloves that the workers wear when working with power hand tools. We will also ask you to use your bare hand to perform the same study activities.

☐ We will ask you to operate actual power hand tools and perform simulated drilling, riveting, nut running, and/or grinding operations. You may choose preferred grip force and push force during operations.

☐ We will ask you to wear occupational exoskeletons when performing aforementioned study activities.

Study measurements
☐ Vibration – We will attach a few surface sensors (look like a small metal cube, non-invasive) at your hand, arm, shoulder and upper back using elastic straps and/or tapes. We will use rubbing alcohol to clean your skin before sensor attachment to ensure good skin attachment. We will also ask you to hold an extra sensor in your palm when you hold onto the shaker or tool handle.

☐ Vibration – We will use a laser vibration detecting device to scan your hand and other body surface areas to assess vibration.

☐ Vibration – We will use two high-speed cameras to take live video on hand and other body parts and use image processing techniques to assess vibration.

☐ Muscle activity – We will attach a few surface sensors (look like a small flat bars of plastic, non-invasive) at your arm and shoulder areas using double-sided adhesive tape. A reference electrode (a wire attached to a self-adhesive circular patch) will be attached to your non-working wrist. We will use rubbing alcohol to clean your skin before sensor attachment to ensure good electric conductivity.

☐ Perceived senses – We will also ask you to report your feeling of the vibration, the amount of effort you spend, and the level of discomfort during vibration exposure.

☐ Posture and body movement – We will attach a few light-reflecting markers (look like a small ball) on your hand, arm, and shoulder using double-sided adhesive tape, Velcro and/or elastic straps. We will use rubbing alcohol to clean your skin before sensor attachment to ensure good skin attachment. We may also attach a cluster of markers using elastic straps over your body.

☐ Posture and body movement – Alternatively, we will attach a few inertial measurement units (looks like a regular sized matchbox) on your arm, wrist, shoulder, back, and hips using elastic straps.

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☐ Fingertip tactile sense – We will ask you to place your fingers on a special device. This device can produce a light amount of vibrations. We will ask you to report your sense of the vibration, for example if you can feel the vibration or not.

☐ Fingertip tactile sense – We will place a device with two tips on your fingers and hand and apply light pressure while you are looking away or blindfolded (i.e., no visual cue). We will ask you to report your sense if one or two tips are contacting your skin.

☐ Photos and/or videos documentations – we will take photo and/or video on you when you are performing study activities.
_______ (your initials) consent for photos and/or videos taken from you.
_______ (your initials) do NOT consent for photos or videos taken from you.

Risks and Benefits
Participation in this study is considered low risk. You may request to stop testing at any time of the study if you want to. You will not be penalized for stopping or withdrawing from the study.

1) We would like to disclose to you that prolonged exposure (like months and years) to high level of hand-transmitted vibration can cause a number of health issues known as hand-arm vibration syndromes, which include permanent loss of fingertip sense, painful white fingers due to blood occlusion, and tissue injuries at the wrist and elbow joints. However, the total amount of vibration exposure you will experience in this study is no more than what a worker may experience in a single-day, 8-hour job shift involving power hand tool use. Therefore, it is unlikely for you to suffer any serious or permanent injury in this study. Additionally, we will control the vibration precisely to ensure you will not be exposed to unnecessary level of vibration. Safety features have been implemented at both the software and hardware levels. However, you may still likely develop one temporary symptom that we will explain to you the next.

2) Temporary numbness (loss of sense) at the fingertips may occur due to vibration exposure. This numbness is actually one outcome measure we want to assess. The numbness is self-resolving in a short period of time, hence temporary, without any extra care.

3) Under the overhead vibration testing conditions, the setup will involve a chance, though extreme unlikely, of object falling risk as the shaker is suspended overhead. We are using a hoist system that can support 10 times of the weight of the shaker. Also, we have a second set of hanging system to secure the shaker in case the hoist system fails.

4) There will be discomfort associated with noises generated from the shaker and power hand tools. We will ask you to wearing noise-reducing earplugs and/or earmuffs to reduce noise exposure.

5) There is a possibility of eye injury using power hand tools and laser vibration detector. We will ask you to wear safety goggles for eye protection during the experiment.

6) Slight discomfort may be present for the use of rubbing alcohol, double-sided adhesive tape, and medical tapes to secure sensors. The discomfort is self-resolving within a short period of

time without any extra care. Also, in this study, we will take acceleration measurement using double-sided tape and waterproof tape to attach sensors to your skin. There is a chance you may develop skin reaction such as lesion to this acceleration measurement setup. We will verbally confirm with you if you feel any discomfort or pain at the acceleration measurement skin sites. Also, we will take sensors off your skin during the break time and observe if there is any developing skin reaction. If yes, we will remove the sensors and we will seek your consent if you are willing to continue the rest of the measurement without the acceleration measurement on the skin. You can choose to not continue without any punishment.

7) Like any study your personal information may be accidentally disclosed. To prevent this risk, your name will be omitted from all data collection sheets and replaced with an ID number. The signed consent form and the key sheet linking ID numbers to you will be locked in a secure file cabinet. All other documentations, paper or electronic, will only include ID numbers. Signed consent forms and the key sheet will be kept at NIU for a minimum of 3 years, after which it will be safely destroyed, making the data totally unidentifiable.

8) The photo and video taking devices don't transmit data wirelessly through public network (for example, a smartphone camera is not allowed for photo/video in this study). Your photo and/or video records will be kept on password protected PC and encrypted storage devices. Your written consent will be obtained before we use your photo/video for publication purposes. We will mask any identifiable features off your photo/video to protect your confidentiality. Unprocessed photos and videos will be erased no later than 3 years after the conclusion of the study.

There are no other reasonably foreseeable risks associated with this study.

The benefits are this study will advance our understanding in transmission of vibration in the hand, arm, and shoulder, particularly the effect of coupling between the hand and tool handles and the effect of working posture (front-of-body vs. overhead). The study will also provide insight into prevention of hand-arm vibration syndromes by implementing proper anti-vibration interventions (e.g., anti-vibration gloves).

Confidentiality [*or ANONYMITY*]

- The records of this study will be kept strictly confidential. Research records in paper form will be kept in a locked file cabinet, and all electronic data will be coded and secured using a password protected computer (or account) and encrypted storage devices. We will not include any identifiable information in any report we may publish without your permission.
- With your permission your photos and/or videos (they will be processed to remove any identifiable features such as face and body marks) will be used for publication purposes. You will be given the opportunity to review and approve any material that is published about you.
- There is a chance that state and/or federal government agencies may audit this study. If this happen, your identity may not be protected.

COVID-19 Prevention

- All researchers will follow state, local, and university guidelines for human interaction
- All participants will be pre-screened prior to conducting face-to-face research
- All researchers will self-screen prior to conducting face-to-face research

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- All researchers will wear masks at all times
- We will provide gloves and masks to participants if requested
- We will follow social distancing – maintain a distance of 6 feet (unless the research requires
- brief contact)
- Researchers will wear gloves if there is direct contact with participants (e.g., during
- application of sensors to skin or assistance with donning and doffing of exoskeletons)
- All sessions will be scheduled so that participants do not overlap
- All applicable research areas and all research equipment will be sanitized after each participant
- All researchers will wash and sanitize hands frequently
- Researchers will keep a list of all participants and who interacted with them to allow for contact tracing

COVID-19 Screening

- We will make sure that both researchers and participants:
- Have not received a diagnosis of COVID-19 in the past 14 days.
- Have not had close contact with someone with a lab confirmed COVID-19 diagnosis in the past 14 days.
- Do not exhibit any of the following COVID-19 symptoms:
  - cough
  - shortness of breath or difficulty breathing
  - chills
  - repeated shaking with chills
  - muscle pain
  - headache
  - sore throat
  - loss of taste or smell
  - diarrhea
  - fever (temperature of 100 or greater)

Compensation

You will not receive compensation for participating in this study.

Your Rights

The decision to participate in this study is entirely up to you. You may refuse to take part in the study at any time. Your decision will not result in any loss of benefits to which you are otherwise entitled to. You have the right to skip any question or research activity, as well as to withdraw completely from participation at any point during the study.

You have the right to ask questions about this research study and to have those questions answered before, during, or after the research. If you have any further questions about the study, at any time feel free to contact the lead investigator Dr. Ting Xia at txia@niu.edu or by telephone at 815-753-1298. If you have any questions about your rights as a research participant that have not been answered by the investigators or if you have any problems or concerns that occur as a result of your participation, you may contact the Office of Research Compliance, Integrity, and Safety at (815) 753-8588.

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Future Use of the Research Data

After removing all identifying information from the data including your name, study ID, and contact information, the data collected from you could be used for future research studies or distributed to other researchers without additional informed consent from you. Your photo/video records will not be used for purposes other than the current study.

☐ I acknowledge.

Your signature below indicates that you have decided to volunteer as a research participant for this study, and that you have read and understood the information provided above. You will be given a signed and dated copy of this form to keep, along with any other printed materials deemed necessary by the study investigators.

____ __________________
Participant's Signature Date

____ __________________
Witness's Signature Date

Northern Illinois University
1/22/2021
Approved by NIU IRB
Void one year from above date

A.2 Front-of-Body posture

Experiment Procedure:

1- **Consent procedure (Explaining the experiment briefly again to the subject and signature of consent form)**

2- **Exoskeleton adjustment and recording of exoskeleton height and holes**

3- **Practice 8 MVC motions**

4- **MVC testing procedures**

1- Clean skin using alcohol pad and mark location using a marker pen (twice)

2- Sensor attachment (9 sensors)

3- MVC trial **- 8 MVC motions:** For each MVC motion: 5sec instruction, 5sec counting, 5sec transition to next MVC motion

4- Save recording

5- 3min rest

6- Repeat steps 3 to 5 for a total of 3 trials

5- **Vibration testing procedures**

1- Accelerometers' attachment (Wrist, Elbow, Shoulder, Neck C7, T10, L3, Exo)

a. Clean skin using alcohol pad and mark location using a marker pen

b. Use circular double-sided tape to attach adapter (equipped with sensor) on skin

c. Place waterproof tape on top of accelerometer

2- Adjust lift height and subject standing position on the force plate for FOB-condition1

a. Use the shoulder and elbow angles to make the adjustment

b. Use tape to mark the foot positions on the force plate

3- Power on Shaker without turning on vibration

4- Put on the exoskeleton

5- Place sensor on exoskeleton

6- Practice feedback for grip and push force

7- No vibration

a. Ask subject to standstill, turn on force amplifiers

b. Ask subject to hold the handle and produce the right grip force (red needle) and push force (blue needle)

c. Subject talk to tester when s/he is ready

d. Data recording for 12 sec

e. Save recording

8- Turn on vibration and repeat step 6 and 7 after 1min rest Without touching the handle in rest time

9- **3min rest**

10- Repeat steps 6 to 8 for a total of 3 trials

11- Change FOB condition 1 to 2 and repeat steps 2 to 10

12- Change exoskeleton and repeat steps 5-11 (wearing 2 exoskeletons and without wearing exoskeleton condition)

A.3 Overhead posture

Experiment Procedure:

1- **Consent procedure (Explaining the experiment briefly again to the subject and signature of consent form)**

2- **Exoskeleton adjustment and recording of exoskeleton height and holes**

3- **Practice 8 MVC motions**

4- **MVC testing procedures**

1- Clean skin using alcohol pad and mark location using a marker pen (twice)

2- Sensor attachment (9 sensors)

3- MVC trial **- 8 MVC motions:** For each MVC motion: 5sec instruction, 5sec counting, 5sec transition to next MVC motion

4- Save recording

5- 3min rest

6- Repeat steps 3 to 5 for a total of 3 trials

5- **Vibration testing procedures**

1- Accelerometers' attachment (Wrist, Elbow, Shoulder, Neck C7, T10, L3, Exo)

a. Clean skin using alcohol pad and mark location using a marker pen

b. Use double-sided tape to attach sensor on skin

c. Place waterproof tape on top of accelerometer

2- Adjust lift height and subject standing position on the force plate

a. Use the shoulder and elbow angles to make the adjustment

b. Use tape to mark the foot positions on the force plate

3- Power on Shaker without turning on vibration

4- Put on the exoskeleton

5- Place sensor on exoskeleton

6- Practice feedback for grip and push force

7- No vibration

a. Ask subject to standstill, turn on force amplifiers

b. Ask subject to hold the handle and produce the right grip force (red needle) and push force (blue needle)

c. Subject talk to tester when s/he is ready

d. Data recording for 12 sec

e. Save recording

8- Turn on vibration and repeat step 6 (a-e)

9- **3min rest**

10- Repeat steps 6 to 8 for a total of 3 trials

11- Change exoskeleton and repeat steps 5-9 (wearing 2 exoskeletons and without wearing exoskeleton)

A.4 Checklist Table for A Study Visit

Subj No	
Consented	

Visit No	1
Date	

	Exo setup		
Exo1			
Exo2			

SubNo.	OH	FOB
sub1	123	123
sub2	231	231
sub3	312	312

SubNo.	FOB	OH
sub4	321	321
sub5	132	132
sub6	213	213

Check All EMG Sensors are attached before start recording								
Ant.Delt	Med.Delt	Pos.Delt	Up.Trap	Latis.Dorsi	Pectoralis	Serratus	Biceps	Triceps
Trial No	SubNo_MVC_ShakerPosition090_EXO0_						file count	Check Mark
1								
2								
3								

Check all Accelerometers are attached before taking pictures								
wrist	**Elbow**	**Shoulder**	**C7**	**T10**	**L3**	**EXO**		
1								
2								
3								
4								
5								
6								

Check all Accelerometers are attached before taking pictures								
wrist	**Elbow**	**Shoulder**	**C7**	**T10**	**L3**	**EXO**		
1								
2								
3								
4								
5								
6								

Check all Accelerometers are attached before taking pictures								
wrist	**Elbow**	**Shoulder**	**C7**	**T10**	**L3**	**EXO**		
1								
2								
3								
4								
5								
6								