Effects of Short-Term Exposure to Hand-Arm Vibration on Physiological Responses and Hand Functions

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短時間の手腕振動暴露が生理応答および手機能に及ぼす影響

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REVILLA, JOSEFA ANGELIE D.

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List of Abbreviations

ANOVA	Analysis of variance
EAV	Exposure action value
ECR	Extensor carpi radialis
ELV	Exposure limit value
EMG	Electromyography
FCR	Flexor carpi radialis
FCU	Flexor carpi ulnaris
FF	Finger flexors
HAV	Hand-arm vibration
HAVS	Hand-arm vibration syndrome
HTV	Hand transmitted vibration
MVC	Maximum voluntary contraction
WBV	Whole-body vibration

List of Publication

Chapter 2

Josefa Angelie D. Revilla, Ping Yeap Loh, & Satoshi Muraki. (2019). Exploratory study on the impacts of handle vibration on the hand and forearm. *Industrial Engineering & Management Systems, 18*(4), 591–599. doi: 10.7232/iems.2019.18.4.591

Abstract

Hand-guided powered equipment is a common source of occupational hand-arm vibration (HAV). In the Philippines, a hand tractor has been found to transmit excessive level of vibration to the farmers. Extended exposure to such vibration can have serious and permanent effects on fundamental hand and arm functions commonly known as the hand-arm vibration syndrome (HAVS). The general objective of this dissertation is to provide new and holistic insights on the physiological stress caused by the cumulative effects of HAV, sustained grip force levels, and two forearm postures commonly applied when operating a dual-handle guided equipment. The main objectives are to characterize the effects on physiological responses and hand functions of short-term HAV: (1) with unmonitored and self-imposed grip force and neutral forearm, (2) with sustained moderate grip force and neutral forearm, and (3) with mild and hard grip forces on two forearm postures. The final objective is to determine the influence of implementing various handle shapes and surface profiles on reducing the harmful effects of HAV.

A preliminary study exploring short-term HAV with unmonitored and self-imposed grip force demonstrated declined forearm muscle activities during grip strength test and higher shoulder discomfort. Nonetheless, to clearly determine the distinctive contribution of vibration, grip level, and posture, the succeeding studies monitored and imposed constant force exertion and forearm posture for each task duration. The first study found that 5-min vibration exposure with sustained moderate grip and neutral forearm leads to temporary reduction of middle finger sensitivity, hand-arm discomfort, and reduced ability to grip consistently. The second study discovered that the cumulative effects of consistently gripping hard on pronated forearm instigates higher wrist transmitted vibration, higher proximal arm discomfort, and lower finger flexors activity through time than hard grip on neutral forearm or mild grip on either forearm posture. Finally, the third study demonstrated that circular and double-frustum handles prompt lower transmissibility and lower grip strength reduction than elliptic handle, while patterned surface profile on elliptic-shaped reduces ring and small finger sensitivity, increases hand area discomfort, and decreases grip comfort.

These findings imply that: (1) short-term HAV exposure can stimulate the onset of peripheral neuropathy and musculoskeletal disorders that may result to temporary grip impairment, (2) grip force level can directly influence the progression of HAVS seen on reduced grip strength and increased upper limb discomfort, (3) poor forearm posture combined with forceful movement can instigate early development of upper limb musculoskeletal injuries, and (4) handle shape can influence vibration transmissibility and force exertion while surface profile can affect sensation and comfort. In conclusion, the development of HAVS can be controlled through preventing intense force exertion even during short-term HAV exposure, consideration of appropriate forearm posture in cases that require forceful hand-arm movements, and implementation of smooth-textured handle grip that reduces the hand and handle contact stress.

Chapter 1. General Introduction

1.1 Vibration in the workplace

In the recent years, vibration in the workplace has been prevalent due to industrial mechanization (Shen & House, 2017; Trotto, 2015). In production management perspective, integrating machine and human capabilities primarily aimed for higher productivity and work efficiency. However, this also steered to continuously convert basic tools and equipment into powered machineries that generate vibration. Transportation, agriculture, forestry, fisheries, construction, mining, and manufacturing are some of the common industries that exposed workers to occupational vibrations (Krajnak, 2018). Generally, there are two common means of vibration exposure: whole-body vibration (WBV) and HAV, which can affect different parts of the human body depending on the contact point. WBV is commonly transmitted to the lumbar spine that can continuously flow to the upper back, shoulders, and neck while HAV is absorbed by the hand before it eventually flows to the upper limbs.

The transportation and warehousing industries utilized various types of transport vehicles to deliver goods and passengers. Due to different road pavements, workers are exposed to random and intermittent WBV while driving. In agriculture, forestry, fisheries, construction, and mining industries, workers are exposed to ride-on machineries like tractors, fishing vessels, and large earth moving equipment such as bulldozers and dump trucks, which also transmit WBV. In general, vibration is a necessary physical factor in all ride-on machineries and the vibration frequency in most vehicles is within 3 to 7 Hz (Harrison et al., 2000; Kuiper et al., 2005; Zamanian et al., 2014). On the other hand, HAV from powered equipment like chainsaws, hand tractors, jackhammers, drills, grinders, and sanders are also present in the above-mentioned industries. The harmful effects of WBV and HAV intensify when integrated with extended period of forceful movements and awkward postures (Giannini et al., 1999; Morgan & Mansfield, 2014; Smets et al., 2010; Thompson et al., 2010; Yung et al., 2017).

1.2 Whole-body vibration

Apart from occupational settings, WBV is also found in sports training and is used as medical intervention especially in physical rehabilitation. It can stimulate muscle activity (Eklund & Hagbarth, 1966), enhance muscle strength and power (Issurin et al., 1994; Issurin & Tenenbaum, 1999; Rehn et al., 2007), and rehabilitate chronic neurological diseases (Chanou et al., 2012), specifically when moderately applied. Vibration frequency, amplitude, and application method are WBV characteristics that can affect muscle strength. In addition, exercise protocols like training type, intensity, and volume can also influence the development of muscular power (Luo et al., 2005).

Nonetheless, the uncontrolled use of and chronic exposure to WBV is consistently stated to have harmful effects on the human body (Buckle & Devereux, 2002; Gerhardsson et al., 2005; Nishiyama et al., 1998). From minor disorders like headaches and dizziness caused by motion sickness to severe neck and back pains from long hours of driving were reported (Boshuizen et al., 1991; Bovenzi, 2005; Bovenzi & Hulshof, 1999; Kumar et al., 1999). As listed in one study, the common sources of occupational WBV are cars, vans, lorries, tractors, buses, forklift trucks, and loaders (Palmer et al., 2000). One of the standard parameters that can be used to quantify vibration exposure is the estimated vibration dose value (eVDV), which is calculated using the frequency, magnitude, exposure duration, and direction of the imposed vibration. The exposure action value (EAV) and exposure limit value (ELV) are also frequently used parameters to classify safe exposure. EAV is the daily amount of exposure in which employers must take act to control contact, while ELV is the maximum level that an unprotected operator may be exposed to in an 8-h period. For WBV, the suggested EAV and ELV is 0.5 m/s^2 and 1.15 m/s^2 (Palmer & Bovenzi, 2015). Furthermore, according to the International Organization for Standardization (ISO 2631-1, 2007), a 10 min/day of WBV training is potentially harmful to the body. Hence, exposure must be regulated within this period.

1.3 Hand-arm vibration

Hand-held powered tools and hand-guided powered equipment such as sanders, drillers, grinders, pneumatic hammers, chainsaws, jackhammers, and hand tractors usually used in the workplace are the primary sources of HAV. These tools and equipment create a wide range of vibration frequency that are transmitted to the hand and arm of the users. The Health and Safety Executive provided a summary of vibration magnitudes of these machines. For instance, hand drills have a vibration magnitude of 2–5 m/s^2, grinders generate 3–10 m/s^2, sanders have 6–14 m/s^2, pneumatic hammers generate 10–29 m/s^2, and chain saws have 3–14 m/s^2 (HSE, 2013). Leisure activities such as cycling and tennis are also other sources of HAV (Chiementin et al., 2013; Cross, 2015; Taylor et al., 2018). Similar to WBV, the International Organization for Standardization (ISO 5349-1, 2001) has set two threshold values for safe HAV. The recommended EAV and ELV is 2.5 m/s^2 and 5 m/s^2 (Palmer & Bovenzi, 2015).

The Canadian Center for Occupational Health and Safety stated that for hand tools generating vibration, the ideal way to limit transmissibility is during the tool design stage through making ergonomically designed handles. However, for existing machineries, which failed to consider this on their design phase, several control measures to reduce the amount of transmitted vibration like anti-vibration gloves for personal protective use (Budd & House, 2017; Hewitt et al., 2016), inclusion of grip support and engine mounts (Binarao et al., 2017; Layaoen et al., 2015; Yap et al., 2016), and redesigning the handlebar structure (Mojica et al., 2016) were investigated. In addition, some guidelines based on common exposure patterns were suggested. For instance, the use of hammer tools for more than 1 h/day or rotary tools for more than 2 h/day may likely surpass ELV while EAV may be exceeded if exposed to certain hammer tools for as little as 15 min/day (HSE, 2005). Thus, exposure duration must be limited within these periods.

1.4 Hand-arm transmitted vibration

Vibration is typically measured using accelerometers, which are attached to the source in various ways. With the help of data analysis software, vibration parameters such as amplitude and acceleration can be calculated and analyzed through using appropriate formulas and equations. In most cases, time-based signals are converted into frequency-based data using Fast Fourier Transform (FFT) because this form of data can provide a more meaningful information such as the frequency bands where peak vibration amplitudes occur and what causes them to happen. In addition, vibration signals can also be measured using tri-axial accelerometers, which record the vibration along the x-, y-, and z-axes. This type of accelerometer can provide a more substantial information about the vibration source. Generally, the total vibration acceleration is computed as:

$$AT_i = \sqrt{{Ax_i}^2 + {Ay_i}^2 + {Az_i}^2} \tag{1.1}$$

where AT_i is the total vibration acceleration, Ax_i, Ay_i, and Az_i are the vibration acceleration measured along the x-, y-, and z-axes on measurement location *(i)*.

Aside from AT_i, another meaningful vibration parameter is the amount transmitted from the source to various locations connected to it. Fundamentally, transmitted vibration is the ratio between the total vibration acceleration measured on the desired measurement location and on the source. For hand-arm transmitted vibration (HTV), the common measurement locations are the hand, wrist, forearm, elbow, upper arm, and shoulder (Layaoen et al., 2015; Revilla et al., 2015; Wen et al., 2019; Xu et al., 2017). The magnitude of effects of vibration on humans depend on the amount transmitted to the body. ISO 5349-1 (2001) enumerates the factors that influence the effects of HTV during working condition. These include the frequency spectrum and magnitude of vibration, exposure duration per working day, and cumulative exposure to date. Theoretically, frequency (in Hz) is the movement of vibration per second that affects the amount being absorbed by the body; magnitude (in m/s^2) is the peak-to-peak distance reached by the movement or the peak distance from some central value to the maximum displacement; daily vibration exposure duration is the time span that the hands are exposed to vibration; cumulative exposure or daily vibration exposure is calculated from the magnitude of vibration and daily exposure duration (ISO 5349-1, 2001). However, the amount of HTV is not just based on the characteristics of the vibration source but also on the coupling of the hand to the source, nature of tasks, and physiological differences such as age, hand volume, and palm thickness (Burström, 1994a; Burström, 1994b; Burström & Lundström, 1994; Carlsöö, 1982; CEN 15350, 2013).

Grip force and arm posture are the most common studied biomechanical factors that influence HTV. Previous studies stated that strong grip force significantly led to higher vibration transmissibility because as force exertion increases, the stiffness of the arm and effective mass of the palm and hand also increase (Burström, 1994a; Carlsöö, 1982; Pan et al., 2018). This makes the vibration to dissipate easily along the hands and arms. However, grip exertion, specifically at maximum level, is influenced by hand-arm posture (Fan et al., 2019; Mogk & Keir, 2003; Richards et al., 1996). The forearm rotation from pronation to supination has distinct effects on grip exertion because these movements affect the position of the finger flexors and other muscles responsible for gripping (Brand & Hollister, 1993). One study suggested that forearm pronation with mild grip force can inversely influence the effects of HAV (Shibata & Maeda, 2008).

To date, there have been no clear investigations about the combined effects of HAV, forceful movements, and awkward postures on some physiological responses and hand functions when operating a dual-handle moving equipment. Although it has been established that continuous exposure to any of these external stressors can lead to serious illnesses and injuries on the upper extremity commonly known as HAVS.

1.5 Hand-arm vibration syndrome

Prolonged and extensive exposure to high level of HAV leads to neurological, vascular, and musculoskeletal injuries, which is commonly known as HAVS (Lundström et al., 2018; Shen & House, 2017; Ye & Griffin, 2011). High frequency vibration from drills, chisels, cutting and milling machines, and chainsaws, is directly transmitted to the fingers and hands and seemed to be the principal cause of neurological and vascular symptoms (House, 2010). Meanwhile, low frequency vibration that is typically transmitted up to the arms and shoulders could be associated with the musculoskeletal discomforts along these areas (Shen & House, 2017). The prevalence among exposed individuals is approximately 50%, which varies by intensity and extent of exposure (Bernard et al., 1998). Some studies also mentioned that HAVS symptoms increased in temperate and cold climates (Burström et al., 2010; US DHHS NIOSH, 1989; US DHHS NIOSH, 1997).

The neurological aspect causes entrapment of median or ulnar nerves that leads to nerve damage and carpal tunnel syndrome (World Health Organization, 2007). It is also characterized by peripheral neuropathy with symptoms such as numbness of the fingers, loss of manipulative dexterity, and reduced sensory perception of vibration, cold and warm sensation, and pain (Lundström, 2002; Nilsson, 2002). The effects of HAV on thermotactile impairment are more common on cold than warm environment (Burström et al., 2008; Hirosawa et al., 1992) and the neurophysiological symptoms seen on affected workers vary from minor to severe within a few years of exposure (Lundström et al., 2018). Basically, the sensorineural effects of HAVS are classified into stages: 0SN–exposed to vibration but no symptoms, 1SN–intermittent numbness, with or without tingling, 2SN–intermittent or persistent numbness, reduced sensory perception, and 3SN–intermittent or persistent numbness, reduced tactile discrimination and/or manipulative dexterity (Brammer et al., 1987).

Meanwhile, the primary effect of HAVS on the vascular system includes vasospasm of digital capillaries, which results to tingling and numbness of the hands and fingers and may lead to vibration white finger (World Health Organization, 2007). In addition, this causes discoloration, pain, and hyperemia of fingers due to poor blood circulation (Herrick, 2012; Shen & House, 2017). Consequently, in some rare cases, the affected fingers may become permanently discolored and they may develop gangrene (Gemne et al., 1987). The Stockholm Workshop scale (previously, the Taylor-Pelmear scale) has been used to classify the severity of vibration white finger. The stages are: 0–no attacks, 1–mild, occasional attacks affecting only the tips of one or more fingers, 2–moderate, occasional attacks affecting distal and middle (rarely also proximal) phalanges of one or more fingers, 3–severe, frequent attacks affecting all phalanges of most fingers, and 4–very severe, as in stage 3, with trophic skin changes in the fingertips (Gemne et al., 1987; Litherland, 1986; Taylor, 1988).

Finally, musculoskeletal injuries caused by HAV include chronic pain on the joints, ligaments, muscles, and tendons of the upper limb (World Health Organization, 2007). Occupational vibration exposures are significantly linked to the development of severe hand, wrist, elbow, shoulder, and neck pain, although the risk is higher on the distal sites like the hands and wrists (Charles et al., 2018; Palmer et al., 2001). These symptoms seem to occur due to direct vibration-induced damage to muscle tissues and local nerves (Necking et al., 2004). Eventually, fundamental hand functions such as grip strength and pinch strength become impaired (Necking et al., 2004; Widia & Dawal, 2011). Furthermore, musculoskeletal disorders are also highly associated with the nature of tasks, which may involve awkward postures, high hand forces, highly repetitive movements, repeated impacts, and heavy and frequent liftings (Bao, 2015).

The tendency to fully develop vibration-related injuries takes several years. For instance, loggers and mechanics are likely to develop HAVS after 17 years and 24 years of continuous exposure to chainsaws and vibrating tools (Youakim, 2012). In general, the latency period is from one year to 40 years depending on the extent of vibration exposure (Shen & House, 2017). In addition, the ISO standard stated that 10% of workers constantly exposed at the EAV may acquire vibration-related disorders over a period of 12 years. Given that it may take years to develop these injuries, once it is acquired, its effects are irreversible especially if neglected (Druga et al., 2007). The impact and severity of HAVS can affect work-related tasks and even daily life activities. Hence, investigating the effects of immediate exposure, particularly during extreme conditions, is deemed necessary so it can be prevented.

1.6 Immediate effects of short-term exposure to HAV

The early effects of short-term exposure to handle vibration are evident on temporary neurological, vascular, and musculoskeletal disorders such as reduction on finger sensitivity, lower grip strength, symptoms of vasoconstriction, higher muscle contraction, and discomfort along the upper extremity. With regards to the neurological aspect caused by HAV, previous research showed that a 30-min exposure caused the vibration perception threshold to increase and numbness and paresthesia to develop (Malchaire et al., 1998; Thonnard et al., 1997). Meanwhile, even a 2-min handle vibration exposure led to a significant reduction on the index and middle finger sensitivity and a significant increase on finger skin temperature, which are early signs of neurological abnormalities (Forouharmajd et al., 2017). In a profound level, HAV was also found to reduce peripheral blood flow and cause vasoconstriction (Egan et al., 1996; Thompson & Griffin, 2009), which may lead to reduced sensitivity and eventually, vibration white finger. Neurological symptoms seemed to be more commonly developed on short-term exposure than vascular symptoms (Bylund, 2004). On the other hand, the onset of musculoskeletal illnesses can be observed on the reduction of hand strength and perceived discomfort caused by muscle fatigue. In one study, it was found that a 5-min and 15-min exposure to handle vibration led to reduced grip strength and increased forearm muscle activity (Widia & Dawal, 2011), which are immediate signs of fatigue development.

Considering the studies of Forouharmajd et al. (2017) and Widia and Dawal (2011), this dissertation set a 5-min exposure duration since the onset of HAVS symptoms seemed to be visible around this period. Moreover, hand tools or hand-guided equipment requiring strong force exertion are commonly operated in bouts or repetitions of a few minutes followed by a certain amount of rest. Overall, a short-term HAV exposure can start to affect fine hand motor performance, which implied that continuous exposure may lead to more serious and permanent illnesses that can ultimately reduce the quality of life.

1.7 Hand tractor in the Philippines

This dissertation was motivated by previous research about hand tractor vibration conducted in the Philippines (Binarao et al., 2017; Layaoen et al., 2015; Mojica et al., 2016; Revilla et al., 2015; Yap et al., 2016). The Philippines is a tropical country and agriculture is one of the major sources of livelihood. According to the Food and Agriculture Organization of the United Nations, from 1999 to 2014, 25–30% of the total labor force were under the four sub-sectors of agriculture (FAO, 2019). In turn, around 17% of the 30-million-hectare Philippine land area are arable land devoted to farming crops (FAOSTAT, 2014). Among the top agricultural commodities, rice and paddy had the highest production value (FAOSTAT, 2015a) and second in terms of production quantity (FAOSTAT, 2015b). Generally, rice farming can be done manually, but land preparation is performed with the help of carabaos or farming machineries. A common farming machinery is the hand tractor, which is a hand-guided powered equipment used to cultivate small and medium-sized farmlands. Normally, operators forwardly guide and push the hand tractor, at a slow pace, to break-up the soil (shown in Figure 1.1). In some rare cases in which the soil is dry and hard, an added downward force is necessary.

A typical hand tractor engine has a speed ranging from 2,400 to 3,600 revolutions per minute or 40 to 60 Hz, which generates vibration. This vibration is transmitted to the upper limb of operators. Some important points that the previous studies in the Philippines focused on include: (1) determining the amount of vibration transmitted to the hand-arm system during actual farming operations using a tri-axial accelerometer attached to the tractor engine, metacarpal, olecranon, and acromion of the subjects (Revilla et al., 2015), (2) investigating the reduction in HTV when a variety of commercially-available handle grips (bicycle or motorcycle handle grips), substitute grip straps (recycled rubber or cloth), and engine mounts were placed on the handle and engine cage during indoor idling set-up (Binarao et al. 2017; Layaoen et al., 2015; Yap et al., 2016), and (3) redesigning and fabricating a new handlebar structure inspired by the initial designs of Bureerat and Kanyakam (2007) to minimize HTV (Mojica et al., 2016). The series of investigations were able to reduce HTV by a significant amount, specifically under laboratory set-up. However, the influence of hand-arm biomechanics during hand tractor operation was yet to be investigated and found on other related studies. Moreover, the cumulative physiological effects of HAV, changes in grip force exertion, and various forearm posture when using dual-handle equipment were not considered because of resource limitations.

Figure 1.1. Measurement of vibration acceleration on the engine, wrist, elbow, and shoulder during actual hand tractor operation.

In addition, there have been no public reports or records in the Philippines, concerning people who acquired or experienced any symptoms of HAVS. While 40% of Filipino workers are involved in agricultural works (CIDA-LGSP, 2003) and several more percentage are working in manufacturing firms, exposure to vibration is prevalent and related injuries are likely to happen. Exposing the workers to prolonged and extreme vibration may reduce their productivity and ability to work efficiently, especially since crop cultivation involved manual activities such as seedbed preparation, pulling and bundling of seedlings, picking of snails or crop pests, and harvesting (BAS, 2004) that require effective hand movements. Essentially, these made way to this dissertation, which focused on the human aspect and the effects of extreme conditions on the physiology and functionality of the hand and arm. Furthermore, this dissertation investigates the influence of various handle grip designs when subjected to a similar pre-imposed condition.

1.8 General objectives and research plan

The long-term impact of HAV has been massively established and various preventive measures, specifically for affected individuals, have been introduced. It is apparent that the hazard and seriousness HAVS poses can greatly affect the daily life activities of an exposed individual. Moreover, the influence of various grip force levels on the amount of HTV and the effects of short-term exposure on hand and arm disorders have also been well-documented. While these studies focused on various hand-arm biomechanics when using single-handle powered hand tools, there are no studies that considered grip force levels and arm postures when operating dual-handle and power-guided machineries. Unlike powered hand tools that mainly require strong grip and flexed or extended elbow for proper handling and control, hand-guided powered machineries involve various grip force levels and slightly bent elbow depending on how to maneuver and guide the equipment as they move. In addition, the combined effect of handle vibration, various grip force levels, and forearm postures during short exposure duration has yet to be explored on either equipment type.

The cumulative effects of these three factors at the early stages of exposure is necessary to identify the onset of HAVS symptoms on various work conditions, especially when involving dual-handle vibrating machineries. Thus, this dissertation aimed to determine the immediate effects of short-term HAV exposure and how they can be controlled through implementing various handle grip designs.

The main objective of this dissertation is to provide new and holistic insights regarding the physical stress caused by the compounding effects of constant handle vibration, sustained grip force levels, and two forearm postures and how various handle shapes and surface textures can influence the effects. The objective of the first study is to explore how short-term handle vibration affects hand performances and forearm muscles when sustained moderate grip force and neutral forearm posture were applied. The second objective is to investigate the effects of two forearm postures and grip force levels on the amount of vibration transmitted to the wrist and elbow, grip strength reduction, forearm muscle activities, and perceived discomfort along the upper extremity. Finally, the third objective is to determine the influence of various handle shapes and surface profiles on transmitted vibration to the hand and wrist, grip strength reduction, finger sensitivity, forearm muscle activities, perceived discomfort along the upper extremity, grip comfort perception, and perceived strength of vibration.

1.9 Structure of the dissertation

Chapter 2 is a preliminary study that examines the short-term effect of handle vibration, with unmonitored and self-imposed grip force and neutral forearm posture, on the hand and forearm muscles. This chapter is an initial investigation that directs Chapters 3, 4, and 5 to further examine the distinctive contribution of handle vibration, grip force level, and forearm posture on the development of HAVS symptoms.

Chapter 3 explores the early effects of short-term handle vibration on the hand and forearm when sustained moderate grip force and neutral forearm posture were employed. This chapter aims to determine the effects of a 5-min vibration exposure on grip strength, pinch strength, finger dexterity, finger sensitivity, perceived discomfort on the upper limb, and activity of forearm muscles namely the extensor carpi radialis (ECR), finger flexors (FF), flexor carpi ulnaris (FCU), and flexor carpi radialis (FCR). To determine the exclusive effects of vibration, two experiment conditions, with the same grip force level and forearm posture, were compared: no vibration task and with vibration task.

Chapter 4 investigates the effects of two forearm postures and grip force levels on transmitted vibration, grip strength reduction, forearm muscle activities (similar to Chapter 3), and perceived discomfort along the upper extremity. Two common arm posture, neutral and pronated forearm, when using a hand-guided vibration equipment paired with mild or hard grip force were examined. This chapter aims to determine which forearm posture poses less harmful effects during tasks requiring mild and hard grip.

Chapter 5 focuses on determining the influence of various handle shapes and surface profiles on transmitted vibration, hand strength and sensation, forearm muscle activities (similar to Chapter 3), perceived discomfort on the upper limb, grip comfort, and vibration strength perception. This chapter aims to determine how three handle shapes: circular, double-frustum, and elliptic with distinct surface profiles: smooth and patterned influenced the cumulative effects of handle vibration, sustained moderate grip force, and awkward forearm posture on the aforementioned parameters.

Chapter 6 is a synthesis of Chapters 2 to 5. This chapter summarizes the findings and provides a holistic discussion based on the individual and cumulative results of the previous chapters. It also includes areas for further study and future plans about this research.

Chapter 2. Exploratory Study on the Impacts of Handle Vibration on the Hand and Forearm

2.1 Introduction

Physical exposure to vibration has been proven to have desirable and undesirable effects on humans (Carlsöö, 1982; Egan et al., 1996; Fuermaier et al., 2014; Schuhfried et al., 2005). For instance, moderately employed WBV can stimulate and improve muscle activities which is widely applied in various sports training and medical field (Cardinale & Wakeling, 2005; Fuermaier et al., 2014; Schuhfried et al., 2005; Torvinen et al., 2002). Although, when too much vibration is transmitted to the human body, vibration-related injuries can manifest. The hand-arm area is one of the most common parts that is being exposed to such vibration level, specifically with the integration of industrial and other modernized machineries in the workplace. The International Organization for Standardization set a threshold (of 1 m/s^2), action (of 2.5 m/s^2), and exposure (of 5 m/s^2) limit value of handle vibration that can be referred to when using vibration machineries (ISO 5349-1, 2001). The exposure limit value is the maximum daily exposure that an unprotected operator may be exposed to (Stellman, 1998), and any amount greater than this gives higher health and safety risks.

Individuals who have been exposed to jackhammers, chainsaws, drillers, and even some dental tools are those who are prone to HAVS. In Europe alone, 25 million workers are exposed to vibration at work and are at risk to the said injuries. While in the US, 2 million workers are exposed to HAV and 50% of them are likely to develop HAVS (Trotto, 2015). Furthermore, 72,000 to 144,000 cases of HAVS have been reported in Canada as of 2017 (Shen & House, 2017). The Health and Safety Executive (2017) stated that there are approximately 3,000 cases of vibration white finger being reported per year. These numbers show that many people have high chances of acquiring vibration-related injuries from their line of work.

Agriculture is one work sector that is known to have significant risk factors when it comes to exposure from vibration equipment such as tractors, lawn mowers, harvesters, chainsaws, and rice-planting equipment (Vallone et al., 2016). Hence, in an agricultural country like the Philippines, where 17% of the 30-million-hectare land area is devoted for agriculture, a significant number of people are exposed to such risks. For instance, research showed that hand tractor operators are constantly exposed to vibration greater than the exposure limit value (Revilla et al., 2015) and this may lead to injuries commonly known as HAVS (Youakim, 2012). HAVS is defined as injuries in the fingers, hands, and arms resulting to numbness, impaired sensitivity, limited dexterity, impaired grip force, and reduced mobility. These are significant hand functions that are necessary to perform daily life activities and work-related tasks, impairing any of them can lead to low quality life.

The tendency to fully develop vibration injuries takes several years. For instance, loggers may develop it after 17 years of exposure while mechanics may develop it after 24 years of exposure (Youakim, 2012). The ISO 5349-1:2001 described it as: *chances are, 10% of workers with 8-h of daily exposure to 2.5* m/s^2 *of vibration magnitude for 12 years are going to acquire vibration white finger*. Aside from the mechanical source of vibration and exposure duration, the amount of vibration transmitted to the body is also influenced by biomechanical factors such as grip strength and possibly other hand-arm posture (Burström, 1994a; Carlsöö, 1982). In the study of Burström and Lundström (1994), they concluded that tight grip and high vibration frequency (> 60 Hz) elicited high vibration absorption.

Although it may take a few years for HAVS to completely manifest, its effects are irreversible once acquired. Thus, it is extremely important to detect its immediate effects in the early stages of exposure. As an initial step, this study explores the effects of vibration on the hand-arm area when a specified grip force is employed. Specifically, it aims to investigate the impacts of a 5-min handle vibration on hand functions, upper limb discomfort, and forearm muscle responses during hand grip strength test and exposure to task with and without vibration.

2.2 Methods

2.2.1 Participants

This study recruited seven young male adults (23.6 ± 2.1 years old) without any long-term exposure to vibration and have not had any recent injuries in the hand-arm area. Mean height and weight are 175.3 ± 5.5 cm and 71.9 ± 7.4 kg, respectively, while hand measurement is presented in Table 2.1. All participants were right-hand dominant based on Edinburgh Handedness Inventory test (Oldfield, 1971).

Table 2.1. Hand anthropometric data of the participants (mean ± SD).

Variables (in mm)	Right	Left
Hand length	186.4 ± 6.8	185.4 ± 6.8
Hand width	81.9 ± 2.7	80.9 ± 2.5
Thumb	59.1 ± 2.6	59.6 ± 2.6
Index finger	69.6 ± 3.9	69.7 ± 4.0
Middle finger	78.0 ± 2.9	77.7 ± 3.2
Ring finger	72.4 ± 2.3	73.0 ± 2.8
Small finger	57.7 ± 2.8	58.9 ± 2.9
Forearm length	254.3 ± 10.5	255.0 ± 8.9
Upper arm length	358.7 ± 11.2	355.7 ± 14.0

2.2.2 Vibration source

A custom-made vibration machine (Sinfonia Technology Co., LTD., Japan) installed with a bicycle handlebar was used as vibration source. The vibration table has a vibration frequency of 60 Hz and can have a maximum load of 10 kg while the bicycle handlebar is made up of iron, has a dimension of 550 x 270 x 100 mm (width, length, and height), and has a mass of 580 g with pipe diameter of 22.2 mm. The bicycle handlebar was attached to the vibration table through the handlebar attachment, which is composed of aluminium as frames, c-clamps as fixtures, and device mounting stand with round brace clamp as handlebar stand (shown in Figure 2.1 (a)).

2.2.3 Experiment procedure

The experiment was conducted in an indoor laboratory set-up. First, the participant was introduced to the objectives of the study, test procedures, equipment to be used, experiment tasks, and experiment duration. After changing to experiment clothing and measuring the height, weight, hand anthropometry, and handedness, electrodes of surface EMG were placed on the FCR, FF, FCU, and extensor digitorum (ED) of the dominant side. Then, pre-task hand tests mainly: (1) forearm muscle responses during maximal grip strength test, (2) 9-hole peg test for finger dexterity, (3) pinch gauge test for pinch strength, and (4) two-point discrimination test for finger sensitivity were performed to assess baseline hand functions (for further details about the hand tests, see pages 23 and 24).

After the pre-task tests, the participant was instructed to rest for 5 min in a sitting position to allow the hands and forearm muscles to relax before the actual task. Then, he was led to stand in front of the machine for 1 min while being instructed on how to grip the handlebar and how to position the arms during the task. The task was to grip the handlebar in a specified arm posture using 50% strength for 5 min under two task conditions: (1) with handle vibration (V) and (2) without handle vibration (NV). There was no specific elbow or wrist angle during task performance and instead, the participant was just asked to position his arm in the manner shown in Figure 2.1 (b) wherein the upper arm was closed to the trunk, the elbow was approximately angled at 145°, the forearm was in neutral position, the wrist was slightly in ulnar deviation and in flexion, and the hand held the handlebar at 50% perceived grip force. The participant was not encouraged to pull up, push down, or apply any force to the handlebar during task performance instead he was only instructed to hold it in static position. This hand-arm posture was employed since it is closely identical as to how two-wheel tractor operators hold the equipment during farming operation.

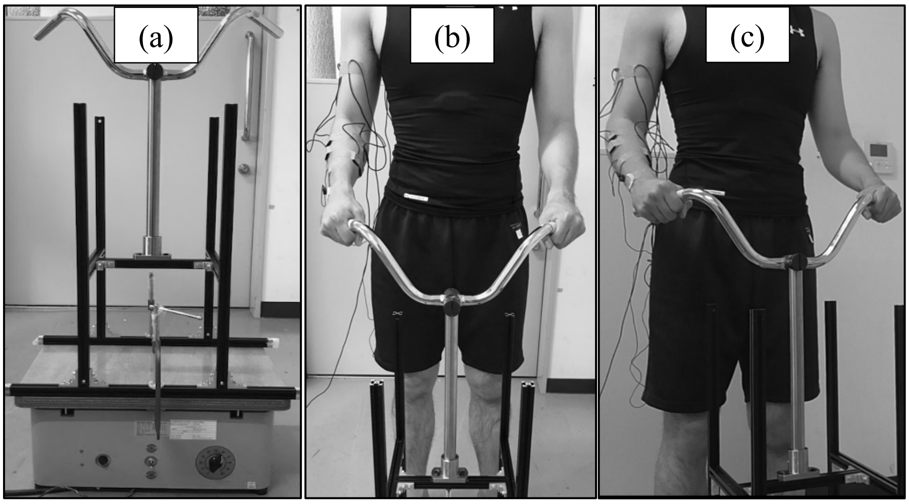

Figure 2.1. Experiment set-up of the preliminary study: (a) vibration source and (b) front view and (c) semi-side view of the hand-arm posture during task performance.

During both task conditions, the responses of FCR, FF, FCU, and ED were transmitted and recorded in PowerLab (ADInstruments, New Zealand) and LabChart software (Version 7.3.8). After the 5-min V task, a 1-min adjustment period was given to the participant as he remained standing in front of the vibration machine while he was asked to rate discomfort felt on the hand, forearm, upper arm, and shoulder. He was also instructed not to rub or wipe his hands because this might affect the results of the succeeding hand tests. Forearm muscle responses during maximal and 50% grip strength test were measured and recorded again, and the other hand tests were performed immediately after. Afterwards, a 5-min complete rest was given before performing the exact same sequence for NV task. The schematized experiment procedure is presented in Figure 2.2.

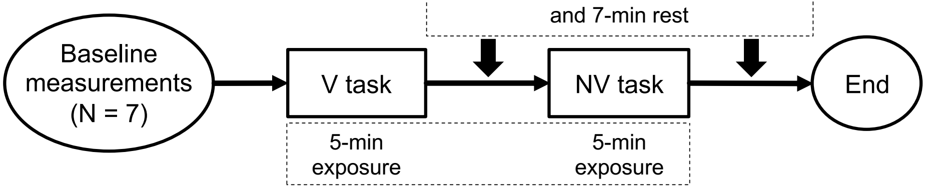

Figure 2.2. Task flow of the preliminary experiment.

2.2.4 Measurements

Data were recorded and categorized into three: pre-task, post V task, and post NV task; while three major tests were analysed: hand tests, forearm muscle responses during grip strength test, and forearm muscle activities during task performance. However, the baseline data were not used for comparison. Instead, only the post-task data were compared since these data can give a clearer indication on the impact of handle vibration.

The dependent parameters were finger dexterity from the 9-hole peg test, lateral pinch strength, finger sensitivity from the two-point discrimination test, subjective discomfort rating, and forearm muscle activities during grip strength test and task performance. On the other hand, the presence and absence of handle vibration was the independent variable.

Hand performance tests

Finger dexterity: A cardboard 9-hole peg panel from The Agency of Design was used to assess finger dexterity of both hands. The participant was instructed to sequentially put the pegs in the designated hole which were numbered from 1 to 9 then remove each of them starting from 9 to 1, as fast as he could. Three actual trials were made for the right hand first, followed by three trials for the left hand and each trial was timed using a stopwatch. If a peg fell on the floor, the trial was stopped and repeated but when it only fell on the table (where the peg board was placed), the time and trial was continued.

Pinch strength: Lateral pinch strength was measured using a B&L Engineering (USA) pinch gauge. Initially, the participant was instructed to have a proper arm posture wherein the elbow was angled at 90° and placed beside the trunk while the forearm was in neutral position, hanging, and not anchored on a table. A lateral pinch using 100% strength was performed three times for the right hand first, and another three trials for the left hand. The researcher supported the opposite side of the gauge as the participant pinched. A rest period of 10 s was given in between trials.

Finger sensitivity: The last hand test was the two-point discrimination test for finger sensitivity. Firstly, the participant was asked to close his eyes and lend his right hand to the researcher. Then, the researcher randomly selected between a single point or any two-point (with 2 to 4 mm distance) from the Touch Test® Two-Point Discriminator (Exacta Precision & Performance, China). A finger (starting from the thumb up to the small finger, one at a time) was poked with these points randomly for seven times and the participant was asked if he felt one or two points. If at least four out of seven times were determined correctly, the next finger was tested. Else, gradually increase two-point distance until the participant correctly determined the number of points being pinned on his finger. The minimum two-point distance that was consistently determined correctly was recorded for that specific finger. Ideally, the greater the two-point distance the lesser tactile sensitivity that finger has. This was repeated for all the fingers on the left hand.

Forearm muscle activities during hand grip test, V task, and NV task

Forearm muscle activities were measured during pre-task-, post V task-, and post NV task-hand grip strength test and during both V and NV task performance. After the placement areas namely the FCR, FF, FCU, and ED of the dominant hand side were located and cleaned, surface EMG electrodes were carefully placed on these forearm muscles. Then, the MVC was measured to normalize the muscle activity data across all participants.

For the grip strength test, the participant was initially instructed to have a proper arm posture wherein the elbow was angled at 90° and placed beside the trunk while the forearm was in neutral position, hanging, and not anchored on a table. It was ensured that the base of the T.K.K.5710B Dynamometer (Takei, Japan) was rested on the heel of the palm and the handle was rested on the middle of the four fingers before the participant squeezed with 100% strength for 10 s. This was done once for the dominant hand then a rest period of 1 min was given. He was again asked to squeeze the dynamometer for 10 s, but this time with 50% strength which was done to practice and familiarize him on how he should hold the handlebar during task performance. During both grip tasks, the participant was instructed to maintain the same force for the 10-s span by looking at a real-time digital value of his grip force. Forearm muscle responses were recorded during the test.

Subjective discomfort rating

After performing each task, a subjective discomfort rating of the hand, forearm, upper arm, and shoulder was asked. Using the Wong-Baker FACES Foundation (2019) pain rating scale, discomfort was ranked from 0 (no discomfort) to 10 (worst possible discomfort). The dominant side was always the main reference during the assessment.

2.2.5 Statistical analysis

Paired t-test was used to compare post V task and post NV task for finger dexterity, pinch strength, subjective discomfort rating, and forearm muscle responses during grip strength test. It was also used for comparing forearm muscle activity during V and NV task. Meanwhile, post V task and post NV task for the two-point discrimination test was compared using Wilcoxon signed-rank test. A non-parametric analysis was used for this hand test since it failed normality (via Shapiro-Wilk test). Lastly, all hand tests for the right and left hand were compared separately between post-task periods and no statistical comparison was made between the two since a natural difference in strength and efficiency was expected between the dominant and non-dominant hand which can cause a misleading contribution to the effects of handle vibration. The level of significance used in the study was 0.05.

2.3 Results

2.3.1 Post-task hand performance tests

Finger dexterity, pinch strength, and finger sensitivity

Paired t-test revealed that finger dexterity and pinch strength did not vary significantly after V task and NV task. This was true for both the right and left hand, although a slightly faster performance in the 9-hole peg test was observed and expected on the dominant hand as compared to the non-dominant hand (shown in Table 2.2).

Table 2.2. Finger dexterity and pinch strength comparison (mean ± SD) (n = 7).

Parameter	Hand side	NV task	V task	*p* (NV vs. V)
Finger dexterity (s)	Right	16.8 ± 1.2	17.1 ± 1.0	0.359
	Left	18.0 ± 2.0	18.2 ± 2.0	0.496
Pinch strength (kgf)	Right	9.5 ± 1.3	9.3 ± 1.5	0.186
	Left	9.7 ± 1.1	9.3 ± 1.3	0.115

Note: NV = no vibration; V = vibration.

On the other hand, Wilcoxon signed-rank test revealed that the mean perceived two-point distance of all fingers did not vary ($p > 0.05$) between post V task and post NV task. Although, the distance of each finger in both post-task periods were within the normal range of less than 10 mm (Moberg, 1990), as presented in Table 2.3.

Table 2.3. Finger sensitivity comparison (in mm, mean ± SD) (n = 7).

Finger	Hand side	NV task	V task	Wilcoxon signed-rank test (NV vs. V)
Thumb	Right	2.4 ± 0.4	2.4 ± 0.5	0.157
	Left	2.4 ± 0.5	2.4 ± 0.5	1.000
Index	Right	2.4 ± 0.5	2.3 ± 0.5	0.317
	Left	2.3 ± 0.5	2.1 ± 0.4	0.317
Middle	Right	2.4 ± 0.5	2.6 ± 0.5	0.317
	Left	2.4 ± 0.5	2.4 ± 0.5	1.000
Ring	Right	2.7 ± 0.5	2.9 ± 0.9	0.655
	Left	2.6 ± 0.8	2.9 ± 0.9	0.414
Small	Right	3.4 ± 0.5	3.0 ± 1.0	0.257
	Left	3.4 ± 0.5	3.0 ± 1.2	0.180

Note: NV = no vibration; V = vibration.

2.3.2 Post-task subjective discomfort rating

There was a significant difference in discomfort perceived on the shoulder between post V task and post NV task, $t(6) = 2.838$, $p = 0.03$. Moreover, it was observed that the hand had the highest discomfort (moderate to severe) among all upper limb area, followed by the forearm (mild to moderate), upper arm (mild to moderate), and shoulder (none to mild), as presented in Figure 2.3.

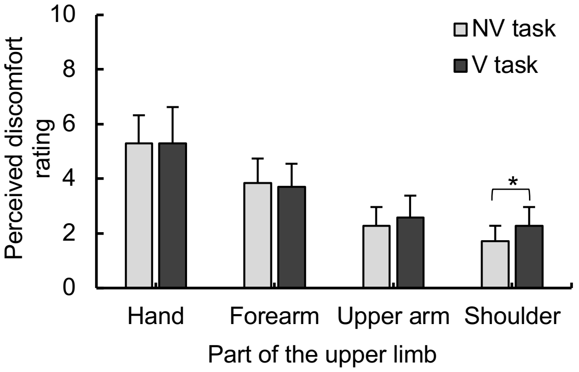

Figure 2.3. Discomfort rating comparison (* $p < 0.05$).
Note: NV = no vibration; V = vibration.

2.3.3 Responses of forearm muscles during grip strength test, NV task, and V task

Paired t-test showed that FCR ($t(6) = -3.057$, $p = 0.022$), FF ($t(6) = -2.656$, $p = 0.038$), and ED ($t(6) = -2.512$, $p = 0.046$) activities on post V task grip strength were significantly lower than that on post NV task (shown in Figure 2.4).

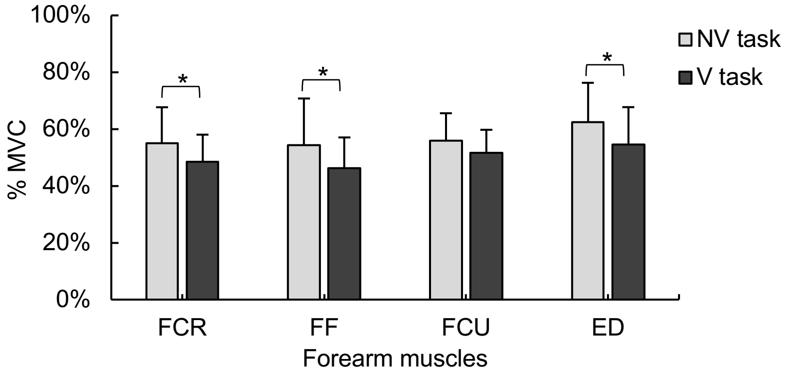

Figure 2.4. Forearm muscle activities during grip strength test (* $p < 0.05$).
Note: NV = no vibration; V = vibration.

On the other hand, although activities of FCR, FF, and ED were relatively higher while FCU activity was slightly lower during V task than NV task (shown in Figure 2.5), no significant differences were found between both tasks.

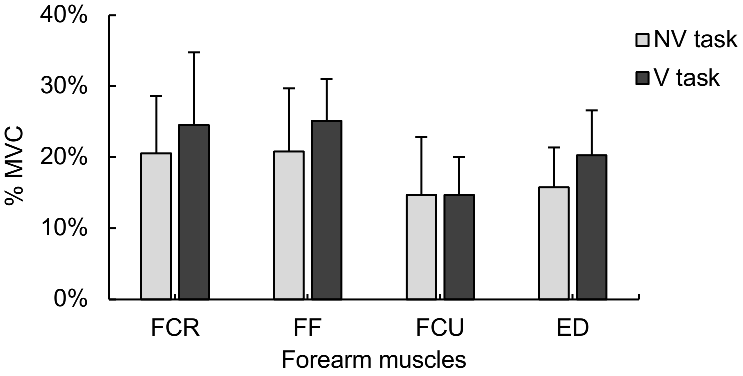

Figure 2.5. Forearm muscle activities during the tasks.
Note: NV = no vibration; V = vibration.

2.4 Discussion

2.4.1 Effects on hand performance

There were no significant differences found between post V and post NV task for all the hand tests. Specifically, an insignificant minimal improvement in the 9-hole peg test performance and an insignificant difference between pre and post V task pinch strength and two-point disk assessment were observed.

The minimal increase in the 9-hole peg performance might have been influenced by another factor such as the human capacity to adapt and learn when subjected to repeated task for a certain period. Since the same simple pattern was assigned for each hand and repeated three times, participants might have memorized the sequence well making it easier to place and remove the pegs, without putting much thought as to where and how to put and remove each of them. Generally, the concept of learning states that as a task is performed repeatedly over time, performance improved because of acquired familiarity and gained knowledge on how to do the task more efficiently. This is most especially applicable when the interval period between each trial is considerably small, similar to the 9-hole peg test performed in this study.

Meanwhile, the insignificant difference in pinch strength after performing V task and NV task might indicate that a 5-min exposure to handle vibration had no effect on finger strength. Post-task pinch strength was within the normal values of 9.8 ± 0.3 kgf (Imrhan, 1991) and 9.6 ± 1.8 kgf (Fernandez et al., 1991) indicated by previous studies. The lack of effect might be due to the differences in muscle group used to perform lateral pinch and hand grip. Intrinsic muscles of the hand are commonly activated during precision-pinch grip, while forearm muscles are used during hand grip. Hence, the lack of engagement of these hand muscles during task performance led to unaltered finger strength.

Lastly, fingertips sensitivity between post V task and post NV task did not differ significantly indicating that the presence of handle vibration had no effect on tactile acuity. This was in contrast with most research specifically with that of Forouharmajd et al. (2017) where they concluded that after exposure to vibration, the two-point distance perceived by the index and middle finger increased by 1 to 2 mm. The difference in results might be correlated with the wrist posture during task performance and the level of grip force employed. In this study, the participants held the handlebar with their wrist in a slightly ulnar deviation and in flexed posture while trying to sustain 50% perceived grip force (shown in Figure 2.6). On the other hand, in the study of Forouharmajd et al. (2017), the wrist was in neutral posture during grip while grip force was not completely specified. This also explains why the index and middle fingers were affected, since median nerves were distressed during neutral grip posture. As for this study, the ring and small fingers were expected to be affected (if there were any) since ulnar deviation of the wrist stresses the ulnar nerves running along the side of the hand and through these fingers. The wrist posture differences lied mainly on the different handlebar structures used in both studies.

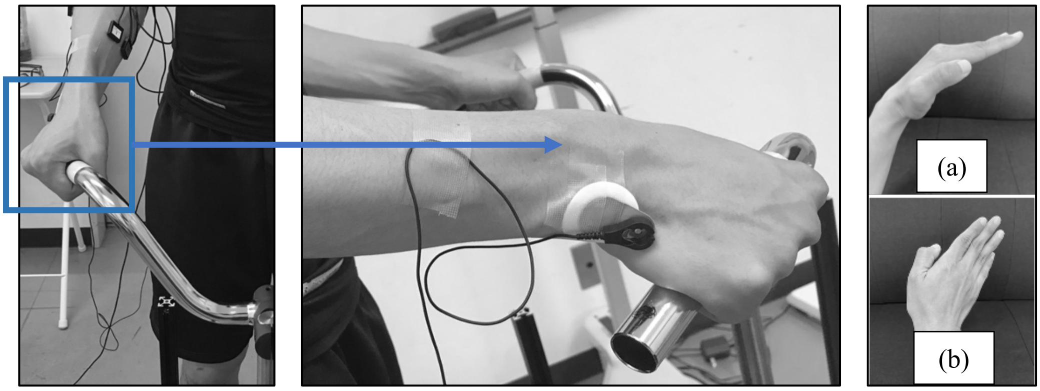

Figure 2.6. Illustration of the wrist in a (a) flexed and (b) slightly ulnar deviated posture during task performance.

In general, the lacking effects of handle vibration on finger dexterity, pinch strength, and finger sensitivity might be caused by the difficulty in sustaining 50% grip force for 5 min. Participants reported that such grip force was hard to sustain for a longer period, hence they were only able to maintain it for the first minutes of performance and gradually let go of their grip as the 5-min mark approached. This might suggest that the inconsistencies in grip force during task performance influenced the outcomes of the hand tests.

2.4.2 Effects on subjective discomfort rating

Perceived discomfort on the shoulder had significant difference between post V task and post NV task. Specifically, the discomfort felt after V task was higher than NV task indicating that handle vibration affected the shoulder area of the participants. This might be due to the instructed upper arm posture during task performance, wherein the shoulder was kept in adduction the entire 5-min. Nevertheless, no force was applied to the handle structure and the hand-arm area was in static.

On the other hand, discomfort on other upper limb area did not vary between post-task periods. This might be due to the same reason that participants let go of the required grip as the tasks approached their end. Nonetheless, a consistent discomfort rating was observed across the upper limb area after performing each task. The hand, being closest to the vibration source, had moderate to severe discomfort while the shoulder, being the farthest to handle vibration, perceived the least discomfort. Previous research concluded that the amount of transmitted vibration during farming operations was highest on the metacarpal, followed by the elbow, then the shoulder area (Revilla et al., 2015). This suggested that higher vibration energy was absorbed by body parts closer to the vibration source, possibly resulting to higher perceived pain or discomfort.

2.4.3 Effects on forearm muscle activities

A significantly lower muscle response was observed for FCR (by 12%), FF (by 15%), and ED (by 13%) on post V task than post NV task grip strength test, which might indicate that handle vibration stimulated higher muscle activity, possibly bordering to development of fatigue. Rota et al. (2014) stated that fatigue may induce a decrease in activity level of triggered muscles which can result to performance decline. In this study, the higher reduction in muscle response during grip strength test after performing V task than NV task might indicate the manifestation of fatigue caused by the presence of vibration combined with trying to sustain a hard grip.

The different forearm muscle responses during grip test were associated with the wrist posture and grip level throughout task performance. For instance, FCR is activated during wrist flexion. During task performance, the wrist was constantly in flexion due to the differences in width between the shoulder and the handlebar structure used in this experiment. On the other hand, FF is stimulated during finger flexion. During the task, it was constantly activated through gripping the handlebar at 50% perceived strength. FCU is activated during ulnar deviation of the wrist, and since the handlebar height (98 cm from the floor) was slightly lower than the waistline of the participants (mean height = 175 cm), the wrist was marginally in ulnar deviation to neutral position for the entire duration. Lastly, ED is triggered during extension of the medial four digits of the hand and contributes to grip relaxation and wrist extension. During the latter minutes of task performance, participants tend to relax their grip due to tiredness and discomfort hence stimulating ED activity. Although there was no significant difference in forearm muscle activities during V and NV task, the presence of handle vibration in V task stimulated signs of muscle fatigue development seen in declined muscle response during grip strength test. As concluded in the study of Souza et al. (2017), grip strength was reduced when wrist extensor muscles got tired of constant activation through repeated exercise.

With a relatively high grip force (of 50%) and integration of handle vibration, more energy was absorbed by the hand-arm system causing FCR, FF, and ED to activate more leading to earlier development of muscle fatigue. This further led to reduced muscle response during maximal hand grip test as presented in Figure 2.4. Meanwhile, FCU was not fully activated since its posture during task performance was relatively in neutral position hence no effect in its activity was observed.

2.4.4 Limitations of the study

While this study only considered muscle activities, determination and quantification of muscle fatigue can also be a good measure to know how handle vibration affects humans in short run exposure. Moreover, the study was not able to monitor the required constant grip force for the 5-min task duration hence possibly influencing the outcomes of the hand tests. Ensuring that grip was constant the whole time can provide results that are mainly associated with the presence of handle vibration. Lastly, the task order was not randomized, defeating the purpose of counterbalancing and possibly influencing some of the findings. These issues will be addressed in succeeding investigations regarding handle vibration.

2.5 Conclusion

This study aimed to investigate the immediate impacts of short-term handle vibration on hand functions, upper limb discomfort, forearm muscle activities during hand grip test, and forearm muscle responses during NV and V task. Finger dexterity, pinch strength, and fingertips sensitivity were not affected by the presence of a 5-min handle vibration. Meanwhile, discomfort rating on the shoulder was significantly higher on post V task than post NV task and the activities of FCR, FF, and ED during maximal grip test were lower after V task than NV task indicating the fatigue effect of short-term handle vibration which affected hand strength. Lastly, forearm muscle activities did not differ significantly during 5-min of V and NV task. It can be concluded that forearm muscle responses during grip test and subjective discomfort rating can be a good predictive parameter when determining the immediate effects of short-term handle vibration.

Chapter 3. Early Effects of Short-Term Vibration and Sustained Grip on the Hand and Forearm

3.1 Introduction

Mechanical vibrations in the workplace have been prevalent in the recent years, and human exposure to WBV or HAV can lead to serious health issues including neurological, vascular, and musculoskeletal disorders (Lundström et al., 2018). Although WBV is more common at work, unwarranted HAV is another issue that needs special attention. Excessive exposure to such vibration can lead to HAVS affecting hand functionalities, such as strength, sensation, and dexterity, which are all essential to daily activities. In the developed nations such as US, Canada, and Europe, where modernized industrial machineries are common, several hundred thousand up to million people are exposed to HAV in their workplace (Shen & House, 2017; Trotto, 2015). One work sector that poses significant risk factors for people working under it is agriculture. Farmers and loggers are highly exposed to mechanical vibrations from machineries such as tractors, rice-planting equipment, mowers, and chainsaws (Vallone et al., 2016). Hand-held olive harvesters generate high levels of HAV (Cutini et al., 2017), and hand tractors exhibit excessive engine vibration (Layaoen et al., 2015) that is above the allowable value.

The International Organization for Standardization has set the threshold limit value (1 m/s^2), exposure action value (2.5 m/s^2), and exposure limit value (5 m/s^2) of hand tool vibrations (ISO 5349-1, 2001). The exposure limit value is the maximum level of vibration that an unprotected operator may be exposed to in an 8-h period (Stellman, 1998), without endangering his health and safety. For hand tractors, control measures such as the inclusion of improvised and commercially available handlebar grip straps, installation of engine mounts, and redesigning and modifying the handlebar structure have been investigated and proven to significantly reduce the amount of transmitted vibrations (Layaoen et al., 2015; Mojica et al., 2016; Yap et al., 2016). In most cases, anti-vibration hand gloves are recommended to reduce HTV. However, some types of gloves are not particularly effective in reducing vibrations responsible for HAVS, and users should not rely on them for full protection. While any means to control vibration should be explored before contemplating on the use of anti-vibration gloves and handle grip straps, the most effective way is to create new working strategies that eliminate vibration exposure (Hewitt et al., 2016; HSE, 2019).

In the Philippines, where 25–30% of the total labor force is working in the agricultural sub-sectors (FAO, 2019), there have been no public reports about people who acquired or experienced any symptoms of HAVS, and the use of anti-vibration gloves has not been legally implemented as a part of personal protective equipment. Crop cultivation involves tasks such as seedbed preparation, pulling and bundling of seedlings, picking of snails or crop pests, and harvesting (BAS, 2004), all requiring hand movements such as gripping, pinching, and efficient dexterity, which can be affected once HAVS is acquired. Although it may take several years for vibration injuries to fully develop with a reported latency period of one to 40 years depending on the extent of vibration exposure (Shen & House, 2017), once they are acquired, their effects can become irreversible specially if neglected (Druga et al., 2007). Thus, it is deemed necessary to detect the effects of vibration, specifically on hand and muscle performance, in the early stages of exposure before they even manifest to anything that can make the operators permanently incapable of working effectively.

As an initial step, this study investigates the early effects of short-term handle vibration on hand performance and forearm muscle activities when sustained moderate grip force was employed. Specifically, it aims to determine the effects of a 5-min exposure to vibration on grip strength, pinch strength, finger dexterity, finger sensitivity, upper limb discomfort, and activities of four forearm muscles namely the ECR, FF, FCU, and FCR.

3.2 Methods

3.2.1 Participants

This study recruited 14 young male adults with a mean age, height, and weight of 24.5 ± 3.5 years, 173.3 ± 5.8 cm, and 65.1 ± 9.4 kg, respectively. The participants were healthy individuals who have not been exposed to any long-term task involving handle vibration and have not had any serious hand-arm injuries. All showed right-hand dominance in the Edinburgh Handedness Inventory test (Oldfield, 1971). Each participant accomplished a written informed consent before the experiment. Furthermore, this study was approved by the Research Ethics Committee of the Faculty of Design in Kyushu University.

3.2.2 Vibration source

A customized vibrating table (Sinfonia Technology Co., LTD., Japan) with a vibration frequency of 60 Hz and amplitude range of 0.5–1.0 mm was used as the vibration source. It was installed with an improvised handlebar that roughly represents a hand tractor handle, as illustrated in Figure 3.1 (a). The improvised handlebar was attached to the table using six c-clamps and composed of an attachment frame, a handlebar stand, and a bicycle handlebar. The height of the handlebar from the floor was 105 cm, which was approximately up to the waist level of the participants.

3.2.3 Experiment procedure

The experiment was conducted in an indoor laboratory set-up at a controlled temperature of 25 °C to prevent palm and arm sweating. Each participant was briefed about the purpose and flow of the experiment and then instructed to wear a heart rate belt and dry-fit short sleeves shirt. Baseline hand tests and grip practice were completed prior to task performance. During grip practice, each participant was instructed to stand and try a moderate or 30% of maximal grip (earlier recorded in the baseline grip strength test) using a hand dynamometer connected to an amplifier that measured the real-time grip force he was exerting. Once the participant was familiar with his 30% grip, he was led in front of the equipment and instructed to hold the handlebar with both hands, as illustrated in Figure 3.1 (a), with the same grip force as that during practice.

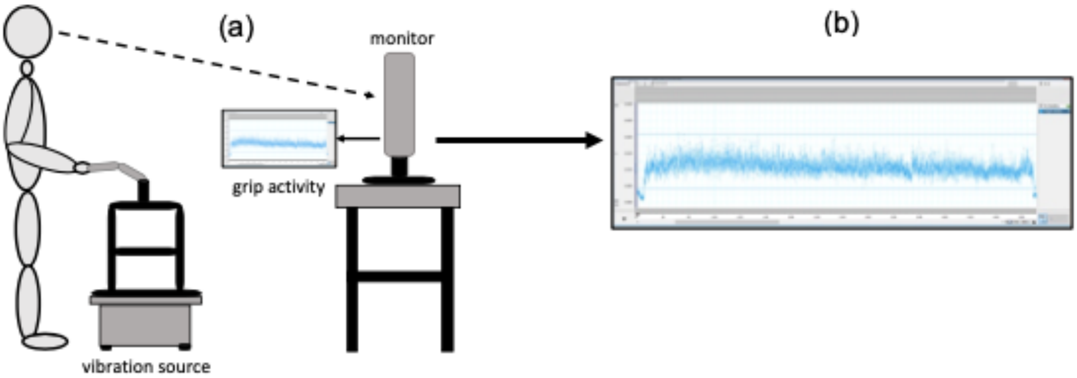

Figure 3.1. Experiment set-up of the first study: (a) schematic diagram of the task performance and (b) a sample target window for monitoring grip exertion.

A moderate or 30% grip exertion was pre-imposed because of (1) the findings on the preliminary study (presented in Chapter 2) and (2) interviews with farmers who operated hand tractors and other agricultural machineries. The preliminary study showed that a 50% self-imposed grip exertion was difficult to sustain, particularly if unmonitored and unassisted. In addition, interviewed farmers stated that they normally grip the hand tractor at about 30-50% during actual farming operation. For these reasons, this study set a moderate or 30% grip force level.

To assist each participant in maintaining the same grip, a monitor that displayed a target window was placed in front of him during task performance. The window showed the activity of one selected forearm muscle, the ECR. From a pilot experiment, ECR activity was found to be directly proportional to the level of grip force. Compared to the activity of flexor muscles, ECR activity is the highest during moderate grip, whereas other extensor muscles are activated during stronger grip (Mogk & Keir, 2003; Norris, 2011).

Thus, in this study, the researcher relied on the activity of ECR as the main representation of exerted grip force. ECR activity during baseline grip strength test represented 100% grip force, and 30% of that was set as the target line. Meanwhile, 10% and 50% of the ECR activity during baseline grip test were set as the lower and upper boundaries (two straight lines shown in Figure 3.1 (b)) within which the ECR activity was instructed to be maintained for the entire task duration.

3.2.4 Experiment design

There were two task conditions in this experiment: no vibration (NV) task, which required holding the handlebar without vibration, and vibration (V) task, which required holding the handlebar in the presence of vibration. The order of tasks for each participant was randomly generated using a MS Excel feature for counterbalancing. After each condition, every participant was prohibited to rub or grasp his hands because this may influence the results of post-task tests. After the tests, a 20-min seated rest was given in order to allow residual effects of the prior task to dissipate, and then the next task was performed exactly in the same sequence. The entire experiment took 2 h for each participant, including preparation, task performance, and rest period.

3.2.5 Measurements

Hand performance tests

Grip strength: Grip strength was measured using the T.K.K.5710B Dynamometer (Takei, Japan) which was connected to the TSA-110 strain amplifier (Takei, Japan). Each participant was instructed to perform two trials of 5 s continuous maximal grip using his dominant hand with 10 s of rest after each trial. During the test, the participant was asked to grip the handle of the dynamometer while standing with the dominant arm placed closely on the side of the trunk, elbow flexed at 90°, and forearm and hand in neutral position. This grip test posture was adapted from a study by Balogun et al. (1991) and it was selected, among three other postures, because it closely mimics the hand-arm posture for holding the handlebar. The researcher supported the opposite side of the dynamometer during the test to ensure that the measured grip strength and muscle activities were not influenced by lifting.

Pinch strength: Pinch strength was measured using a pinch gauge (B&L Engineering, USA). Initially, every participant was taught how to perform lateral pinch and was allowed to practice before the actual test. During the test, the participant was asked to sit down with the dominant arm placed on the side of the trunk, elbow flexed at 90°, and forearm in the neutral position and pinch with the thumb pad on the top and lateral aspect of the index finger at the bottom while the researcher supported the opposite side of the pinch gauge. This posture was adapted from a study by Mathiowetz et al. (1985a). A total of three trials with 5-s rest between two trials were performed.

Finger sensitivity: In this study, the two-point discrimination test was performed to assess tactile acuity using a Touch Test® Two-Point Discriminator (Exacta Precision & Performance, China). Each participant was instructed to close the eyes, lend the non-dominant hand to the researcher, position the hand in supination and rest it on top of a soft cloth placed on a table, and determine the number of pin points (either one or two points, being imposed by the researcher using the two-point disk) perceived by each of the fingers. The researcher started with the thumb and poked it for seven times randomly with either a single point or two points separated by 2-mm distance on the two-point disk. After each time, the participant was asked if the perceived point was one or two. If the points were determined correctly at least four out of seven times, the next finger was assessed, or else, the researcher stayed on the same finger and gradually increased the distance between the two points (e. g. from 2 to 3 mm and so on) until the participant could consistently discriminate two points prodded on the finger. The minimum distance between the two points that was consistently determined as two points was recorded. An acceptable distance indicating useful finger proprioception and tactile gnosis is at most 10 mm (Moberg, 1990). Notably, the non-dominant hand was assessed in this test to avoid fatigue induced by continuous testing. The dominant hand was used on the previous tests and when continuous testing is done on the same hand, fatigue may alter the results.

Finger dexterity: The last test was performed to assess for finger dexterity using a simple peg placement sequence on the 9-hole peg cardboard, which was adapted from a study by Mathiowetz et al. (1985b). Every participant was instructed to put and remove the pegs from holes numbered one to nine. The participant was allowed to practice before the actual trial to gain familiarity. There were three actual trials, which were timed using a stopwatch, with 10 s of rest between two trials. If a peg fell on the floor, the trial was stopped, and repeated from the start resetting the time on the stopwatch. On the other hand, if it fell on the table, the actual trial was continued. For this test, the non-dominant hand was used again for the same reason as stated in the previous subsection.

Heart rate

A Polar H10 heart rate sensor belt (Polar Electro Oy, Finland) was used to record the heart rate during the tasks (5 min in the standing position) and rest period (20 min in the sitting position). Initially, each participant strapped the belt tightly just under the chest with the polar sensor in the middle of the chest. To start monitoring, the researcher connected the sensor to Polar Flow 3.3.4 (Polar Electro Oy, Finland) via Bluetooth. All data were recorded and retrieved in the application.

Subjective discomfort rating

Subjective discomfort rating from 0 (no discomfort) to 10 (worst possible discomfort) from the Wong-Baker FACES Foundation was used to assess any discomfort on the fingers, hand, forearm, elbow, upper arm, and shoulder of the dominant side before and after performing each task.

Forearm muscle activity

Four forearm muscles namely the ECR, FF, FCU, and FCR were examined. These forearm muscles have substantial roles on power grip. The flexor muscles in the hand and forearm create grip strength while the extensor muscle of the forearm stabilizes the wrist (Waldo, 1996). Essentially, ECR and FCR activate during wrist extension and flexion, FF activates during finger flexion, and FCU activates during wrist ulnar deviation.

Initially, the researcher cleaned the superficial layer of these muscles using skin preparation gel (Nihon Kohden, Japan) and alcohol before attaching the BA-U410m surface bipolar active EMG electrodes (Nihon Santeku, Japan) in line with the muscle fibers. The surface electrode on the ECR was attached around the 1/3 point of an extended line from the lateral end of the elbow crease to the middle of the wrist, with the forearm in pronation. For FF, it was placed on the 1/2 point of an extended line from the medial epicondyle of the humerus to the styloid process of the ulna, with the forearm in supination. For FCU, it was attached around the proximal 1/3 point of an extended line from the posterior portions of the medial epicondyle to the styloid process of the ulna. For FCR, it was placed on the 1/2 point of an extended line from the lateral aspect of the bicep tendon at the elbow crease to the pisiform bone. Finally, a ground or reference electrode was attached on the styloid process of the ulna.

Prior to task performance, the MVC of each muscle was measured. During the MVC test, each participant was instructed to sit and place the dominant hand side on the table with the elbow flexed at 90°. The MVC of ECR was measured by positioning the forearm in pronation and extending the wrist upward with maximum force as the researcher resist the movement by placing pressure on the dorsal part of the participant’s hand. For FF, it was measured by positioning the forearm in neutral and maximally gripping a dynamometer. For FCU, it was measured by positioning the forearm in supination and adducting the wrist with maximum force as the researcher resist the movement. Lastly, for FCR, it was measured by positioning the forearm in supination and flexing the wrist upward with maximum force as the researcher counteract the movement by putting pressure on the participant's palm. The MVC tests were done three times for each muscle. Each test lasted for 5 s and a 10-s rest between trials was given.

The EMG signal was amplified using a BA1104m bio-instrumentation amplifier (Nihon Santeku, Japan) before it was transmitted to ML880 PowerLab 16/30 (ADInstruments, New Zealand) at a sampling rate of 1 kHz and recorded in LabChart 7.3.8 (ADInstruments, New Zealand) with a band-pass filter of 10–350 Hz (Conrad & Marklin, 2014; Kong & Lowe, 2005a). For the MVC test, the root-mean-square (RMS) of the filtered EMG signal taken from the middle 3 s was calculated in LabChart. The maximum among the three trials was considered as the measured MVC. Similarly, the RMS of muscle activities during each task were also computed. The normalized muscle activity or % MVC, which is the ratio of the actual muscle activity during each task and the measured MVC, was computed in MS Excel and was used for comparisons.

3.2.6 Statistical analysis

Since the same set of participants performed NV task and V task, paired t-test was used to compare the results of hand tests, apart from two-point discrimination test results, which failed normality via Shapiro-Wilk test ($\alpha = 0.01$), and heart rate. On the other hand, two-way repeated measures ANOVA was used to assess the effect of exposure time and vibration on forearm muscle activities. The Greenhouse-Geisser correction was applied when the data violated the assumption of sphericity, while the Bonferroni correction was accounted for multiple comparisons. For the subjective discomfort rating and two-point discrimination test, Wilcoxon signed-rank test was used to assess the difference between post NV task and V task. Partial eta squared was included to indicate the effect size. The SPSS Statistics 25.0 (IBM, USA) was used for all statistical computations.

3.3 Results

3.3.1 Hand performance tests

Grip strength, pinch strength, and finger dexterity

Mean grip and pinch strength after performing either NV task or V task were lower than their mean baseline values, while finger dexterity was relatively unchanged. Meanwhile, paired t-test revealed no significant differences between the post NV task and post V task results of these hand tests (shown in Table 3.1).

Table 3.1. Comparison between post NV and V task grip strength, pinch strength, and finger dexterity values (mean ± SD) (n = 14).

Parameter	Baseline	NV task	V task	*p* (NV vs. V)
Grip strength (kgf)	39.3 ± 7.7	33.6 ± 7.6	33.3 ± 7.0	0.856
Pinch strength (kgf)	9.8 ± 1.0	8.7 ± 1.3	8.8 ± 1.0	0.483
Finger dexterity (s)	19.0 ± 1.9	18.9 ± 2.2	18.9 ± 1.9	0.846

Note: NV = no vibration; V = vibration.

Finger sensitivity

The differences between baseline and post-task two-point distance were marginal for all fingers except for the ring finger, which had a significantly higher value after NV task. Wilcoxon signed-rank test showed that the middle ($Z = -1.732$) and ring ($Z = -2.236$) fingers had significantly different two-point distances after NV and V tasks. The middle finger had a higher two-point distance after V task than NV task, while the ring finger showed the opposite result. All other fingers did not show any significant changes between NV and V task results (shown in Table 3.2).

Table 3.2. Comparison between post NV and V task perceived two-point distances (mean ± SD) (* $p < 0.05$; $^{\#}p < 0.10$; n = 14).

Finger	Baseline (mm)	NV task (mm)	V task (mm)	*p* (NV vs. V)
Thumb	2.1 ± 0.4	2.1 ± 0.3	2.0 ± 0.0	0.317
Index	2.1 ± 0.3	2.1 ± 0.3	2.0 ± 0.0	0.317
Middle	2.2 ± 0.4	2.1 ± 0.4	2.4 ± 0.5	0.083 $^{\#}$
Ring	2.3 ± 0.5	2.9 ± 0.5	2.5 ± 0.5	0.025 *
Small	3.0 ± 0.6	2.9 ± 0.7	2.9 ± 0.5	0.564

Note: NV = no vibration; V = vibration.

3.3.2 Heart rate

During both NV and V tasks, heart rate was higher than that during rest period (77.7 ± 9.4 bpm). Meanwhile, heart rate measured during NV task and V task (NV task = 87.5 ± 13.5 bpm and V task = 88.5 ± 13.1 bpm) did not differ significantly ($p = 0.465$).

3.3.3 Subjective discomfort rating

Perceived discomfort increased to mild and moderate after either NV or V task. Particularly, discomfort on the hand ($Z = -2.565$, $p = 0.01$) and elbow ($Z = -1.890$, $p = 0.059$) were significantly higher after V task than NV task. Meanwhile, all other hand-arm areas did not show any significant differences (shown in Figure 3.2).

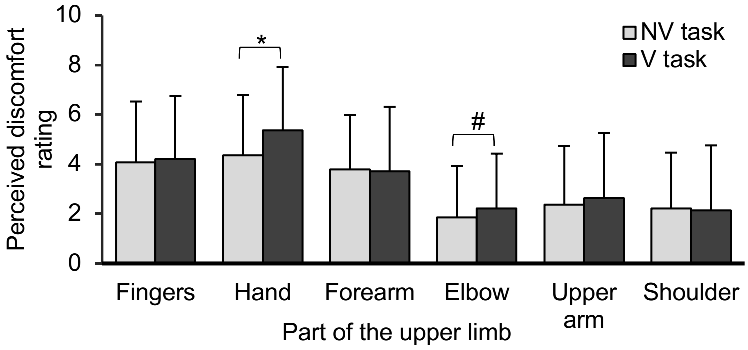

Figure 3.2. Comparison between post NV and V task subjective discomfort ratings (* $p < 0.05$; $^{\#}p < 0.10$; n = 14).
Note: NV = no vibration; V = vibration.

3.3.4 Forearm muscle activities

Mean ECR activity

In this study, ECR activity was monitored and used as the representation of grip force level. Each participant was encouraged to maintain a grip at 30% MVC throughout the 5-min task duration. Hence, ECR activity did not deviate very much from 30%, as shown in Figure 3.3. Moreover, two-way ANOVA confirmed that ECR activity was not influenced by exposure time, but it was affected by handle vibration ($F(1,13) = 5.608$, $p = 0.034$, $\eta^2 = 0.301$). Specifically, it seemed lower when handle vibration was integrated.

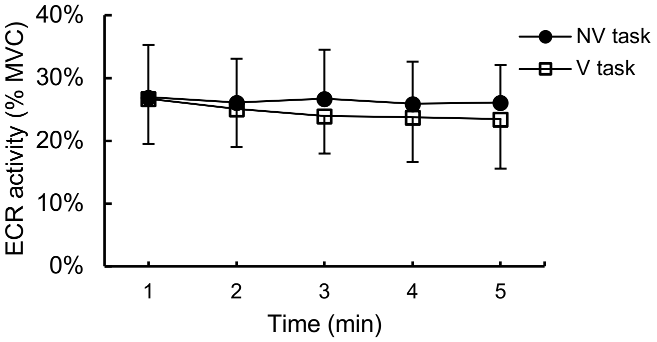

Figure 3.3. A time plot of ECR activity during NV and V tasks.
Note: NV = no vibration; V = vibration.

Mean activities of FF, FCU, and FCR

Two-way repeated measures ANOVA revealed that exposure time affected the FF ($F(1.265,12.655) = 7.720, p = 0.012, \eta^2 = 0.436$, n = 11), FCU ($F(1.598,15.976) = 10.958$, $p = 0.002, \eta^2 = 0.523$, n = 11), and FCR ($F(1.421,17.051) = 7.131, p = 0.010, \eta^2 = 0.373$, n = 13) activities, whereas vibration did not influence the individual muscle activity. The muscle activities during both tasks as a function of exposure duration had a decreasing trend as shown in Figure 3.4. Several outlier data for FF, FCU, and FCR were removed.

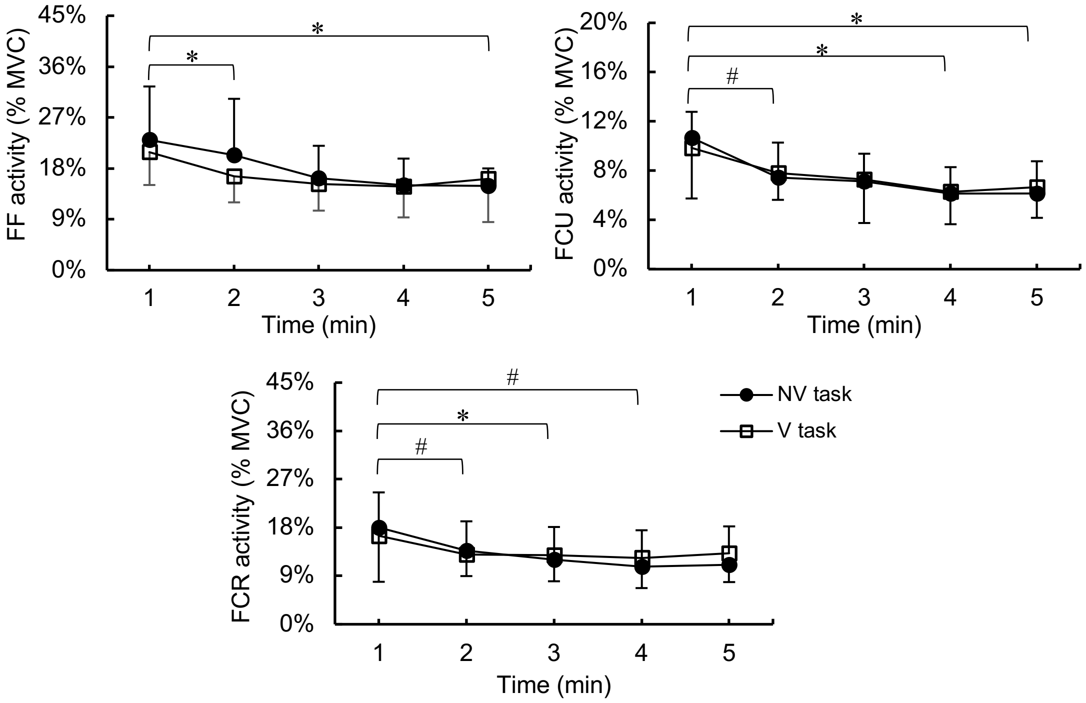

Figure 3.4. A time plot of forearm muscle activities during NV and V tasks ($* p < 0.05$; $^{\#}p < 0.10$).
Note: NV = no vibration; V = vibration.

3.4 Discussion

Long-term exposure to mechanical vibration from hand-held equipment may cause permanent injuries. This study aimed to investigate the early effects of short-term vibration when sustained submaximal grip force was employed. Several hand tests, that assessed hand functions essential to humans, were analyzed after the exposure to HAV. Forearm muscle activities were observed to study the influence of vibration and exposure time on muscle forces. Heart rate was measured to determine the effect of vibration on the sympathetic nerve activities, and discomfort in the upper limb was rated to investigate the perceived physical workload.

3.4.1 Effects on fundamental hand functions

Grip and pinch strength

After performing NV and V tasks, grip and pinch strength were lower than their baseline values. Even without handle vibration, maintaining submaximal grip (via submaximal contraction of ECR) for 5 min was reportedly hard and tiring, which might have resulted in 14.3% and 11.4% reduction in the mean grip and pinch strength. These observations were similar to those of Souza et al. (2017) who stated that fatigue of the wrist extensor muscles decreased grip strength by 16.1% and lateral pinch strength by 16.5%. Meanwhile, both hand strength tests showed no significant differences between post NV and V task results that is similar to the previous study of Revilla et al. (2019), indicating that vibration had very minimal effect on these hand performances. On the contrary, some research findings showed a decrease in grip strength after using bench and electric drills for 5 and 10 min (Widia & Dawal, 2011), respectively, or stone crushing drill for 1 h (Rashid et al., 2018). These differences might be due to variations in the grip force, exposure duration, and applied downward force during task performance. In both of those previous studies (Rashid et al., 2018; Widia & Dawal, 2011), a stronger grip was required to push the drill into the wood or to push the stone crusher into hard stones in the presence of equipment vibration for at least 5 min. This led to a higher vibration exposure and transmission from the equipment to the hands and forearms, which may have caused a more tired upper limb. In contrast, this study imposed a static submaximal grip (30% MVC) and no specific downward force was applied to the handle during exposure, which may have contributed to the lacking effect of vibration on hand strength.

Finger dexterity

Finger dexterity was not affected by either sustaining moderate grip or the presence of handle vibration. In accordance to other study, the researcher used the 9-hole peg test to quantify finger dexterity and observed similar findings (Revilla et al., 2019). Thonnard et al. (1997) reported that a 30-min exposure to an electric sander did not reduce the performance of grip-lift movement and performance on the Purdue peg-board test. Similarly, Malchaire et al. (1998) found that a 32-min handle vibration did not display any effect on dexterity which was quantified using the Purdue peg-board test.

Finger sensitivity

In this study, the task required cylindrical grip with the ring and small fingers sharply bent and rotated horizontally to the maximum extent (Landsmeer, 1962). The importance of ulnar digits in gripping was further emphasized by Methot et al. (2010), who found that grip strength significantly decreased as ulnar fingers were excluded from grip. Meanwhile, handle diameter also influenced finger forces during grip, specifically the middle finger had the highest contribution to total grip finger force (for handle diameters of 25–50 mm), followed by the ring (which showed slightly increased force contribution as the diameter decreased), index, and small fingers (Kong & Lowe, 2005a). With the active participation of the ring and middle fingers in gripping smaller cylindrical handle, the changes found in their tactile sensitivity after NV or V tasks were apparent.

Influence of 5-min sustained grip: There was no significant difference between baseline and post NV task middle finger sensitivity, but a significant reduction of the ring finger sensitivity was observed after NV task, indicating the effect of sustained moderate grip. During task performance, intermediate and proximal phalanges were presumed to have large contact with the handlebar due to the small diameter. However, the required grip posture might have caused the ring finger to have higher grip force contribution than the other fingers, which might have led to significantly lower sensitivity due to prolonged vasoconstriction than that of the other fingers. A study by Bovenzi et al. (2006) found that applied push force directed to the fingertip significantly reduced finger blood flow. In the long term, reduced blood flow may lead to numbness or impaired finger sensitivity.

Influence of handle vibration: Meanwhile, middle finger sensitivity was significantly lower after V task than after NV task. As the middle finger has a relatively higher grip force contribution than the other fingers, the combined effect of contact force and handle vibration reduced its sensitivity possibly due to a high absorption of vibration. This finding was similar to that by Forouharmajd et al. (2017) who stated that the two-point distance perceived by the index and middle fingers increased by 1–2 mm after exposure to vibration. Moreover, in the study by Bovenzi et al. (2006) and Griffin et al. (2006), blood flow in the middle finger significantly decreased when vibration was integrated during force application on the finger or palm, probably due to high vibration absorption. In the long term, continuous vasoconstriction can lead to numbness or reduced sensitivity, similar to the findings of this study.

On the other hand, it was remarkable that ring finger sensitivity was significantly improved after integrating handle vibration. Several studies found that imperceptible vibration can improve the sensitivity of finger pads (Collins et al., 1997; Kurita el at., 2013; Liu et al., 2002). Specifically, vibration below the sensory threshold significantly improves tactile acuity (Wells et al., 2005), whereas that above the sensory threshold is supposed to decrease sensation (Collins et al., 1997). This study employed suprathreshold vibration stimulus, which should have caused a reversed effect. So far, there has been no study that explained improved finger sensitivity in the presence of suprathreshold vibration directly imposed on the finger pad or palm. The findings in this study might be partially explained by the variation in the grip level during task performance. It seemed that a slightly higher grip force was exerted during NV task than during V task. This might have caused sensitivity of the ring finger after NV task to be significantly lower than that after V task. Table 3.2 shows that the sensitivity of the ring finger after V task is slightly lower than the baseline sensitivity. This suggests that the presence of handle vibration combined with sustained grip had marginally affected its sensitivity. However, as less grip force was employed during V task, the influence of vibration became subtle, which led to the absence of apparent effect.

The lacking effects of handle vibration on the other fingers might be attributed to grip force and vibration frequency. It was concluded that a tight grip and high vibration frequency (> 60 Hz) elicited high vibration absorption (Burström & Lundström, 1994; Reynolds & Soedel, 1972). As a result of exposure to vibration in the 80–150 Hz frequency range, the skin vibrates easily, which causes vibration to propagate on the skin surface and leading to acute tactile impairment (Sorensson, 1998).

3.4.2 Effects on heart rate

The effect of WBV on heart rate variability has been extensively studied, whereas the relationship between HAV and heart rate has been rarely investigated. In this study, it was found that heart rate during NV and V tasks was higher than the resting value, however no significant difference was seen between the two tasks. This suggests that the required grip level during task influenced heart rate, while HAV had minimal effect on its value.

In the study of Dawal et al. (2008), they explained that vibration during manual drilling increased peripheral vascular resistance, leading to high blood pressure and low blood circulation, requiring heart rate to increase and be able to meet the oxygen requirement of the body. Although Dawal et al. (2008) did not compare task performances in the presence and absence of vibration, their findings suggested that a physically demanding task integrated with handle vibration could increase heart rate. Meanwhile, Yung et al. (2017) found that heart rate increased after a physically demanding work, whereas it decreased after exposure to seated WBV. These related studies might indicate that a physically tiring task can significantly elevate heart rate, while the integration of vibration alone has very minimal contribution.

On the other hand, some evidences show that other sympathetic nerve activities, such as blood flow and perspiration, are affected by handle vibration (Okada et al., 1991; Sakakibara et al., 1990). From existing research, it is evident that high level of vibration, even when applied to the hand for a short duration, can affect the sympathetic nervous system, although this study failed to show this while using heart rate as a determinant.

3.4.3 Effects on upper limb discomfort

Baseline subjective discomfort rating was considerably lower than the rating after either tasks, suggesting that 5 min of sustained submaximal grip caused discomfort, possibly due to high physical workload. Moreover, it was evident that the participants had more discomfort in their hand and elbow after V task than after NV task. The hand had the highest discomfort as it had the maximum contact with the vibrating handlebar, which caused it to absorb high amounts of vibration. In a previous study, it was determined that the metacarpal absorbed the highest vibration transmitted from the hand tractor during farming, followed by the elbow and shoulder (Revilla et al., 2015). This explains why the metacarpal had moderate discomfort, whereas the elbow and shoulder were only rated with mild discomfort. On the other hand, the elbow which is a connecting joint of the forearm and upper arm, also had a significantly higher discomfort after V task than after NV task. Mechanically, a connecting point of a structure experiences great stress when subjected to vibration. Consequently, in a similar study of Revilla et al. (2015), they found a significantly different vibration acceleration on the elbow, among subjects, due to elbow angle differences during farming operation. This suggests that the elbow angle during task performance affected the amount of absorbed vibration and, possibly, the perceived discomfort. Meanwhile, the lack of discomfort in the other upper limb areas might be due to the grip force level, exposure duration, and magnitude of handle vibration.

3.4.4 Effects on forearm muscle activities

As the participants were instructed to sustain submaximal ECR contraction to represent 30% of their maximal grip for 5 min, ECR activity was unaffected by the exposure time. However, the presence of vibration affected ECR contraction. Specifically, a lower ECR activity was found during V task than during NV task, indicating that it was more difficult to sustain similar levels of grip force during constant and voluntary ECR activation at the submaximal contraction due to integration of vibration.

In theory, muscle fatigue decreases muscle performance and activity level as a result of intense and repeated use of the triggered muscle (Allen et al., 2008; Rota et al., 2014). Neuromuscular fatigue is manifested through central fatigue, which signifies a decrease in the voluntary activation of a muscle due to reduction in the discharge rates of recruited motor units, or through peripheral fatigue, which indicates a reduction of muscle fibers' contractile strength and alterations in the transmission of muscle action potentials (Abd-Elfattah et al., 2015; da Silva et al., 2014). In most cases of fatigue, EMG amplitude increases as the muscles get tired due to the surge of newly recruited motor units and changes in their firing rate (da Silva et al., 2014; Kallenberg et al., 2007). In sustained MVC, muscle torque is the highest at the beginning and gradually falls throughout the remaining contraction duration. However, in sustained submaximal activation, the number of recruited motor units at the start depends on the required contraction and increases over time to sustain the said contraction due to reduction in the force generating capacity of the initially recruited motor units (Hoffman et al., 2009; Löscher et al., 1996).

The brain's intention to sustain the same muscle torque over time are transmitted to these above-mentioned neuromuscular behaviors, which eventually leads to increased EMG signal. In contrast, if the brain does not intend or know how to maintain the same force over time, it signals through the same pathways, leading to muscle force reduction and decreased EMG signal. In general, EMG signals can be fatigue-induced (da Silva et al., 2014; Kallenberg et al., 2007) or force-related (Pajoutan et al., 2017), depending on the brain's intention. Furthermore, EMG signal and muscle force are often assumed to have a linear relationship in a non-fatigued state of muscles (Dideriksen et al., 2010); however, this relationship changes as muscles get tired.

Therefore, as evident by the ECR activity during NV and V tasks, the participants seemed to have decreased their grip force when handle vibration was integrated in the task. Although their grip was consistently around 30% of MVC during the entire duration of both tasks, the results indicated that on the average the participants' intention to sustain the same level of grip for 5 min was lower during V task than that during NV task, possibly due to the discomfort brought by handle vibration. This was further supported by the discomfort rating on the hand which was significantly higher after V task than after NV task. On the other hand, decreased EMG signal could also be attributed to the fact that the participants did not have long-term exposure to handle vibration and that the task performed in this study was a new experience for the participants, making it quite difficult and uncomfortable for them to perform. In general, the lower ECR activity during V task reflected the participants' lack of intention or ability to hold the handlebar with sustained grip because of the difficulty caused by handle vibration.

On the other hand, the FF, FCU, and FCR activities were affected by the exposure time but not by the presence of vibration. Regardless of handle vibration, the activities of these three forearm muscles showed a decreasing trend (shown in Figure 3.4), which might also be associated with reduction in the muscle force as the task proceeded. During finger flexion, FF was activated, which was required to grip the handlebar. During ulnar deviation of the wrist, FCU was activated, and during wrist extension or flexion, FCR was stimulated, which was demanded due to the handlebar structure. A common notion for a non-fatigued muscle is that a linear relationship exists between its EMG amplitude and muscle force. In this case, as the task progressed, the force generated by these muscles to sustain the same posture reduced, resulting in decreased EMG signal, possibly due to the brain's intention or ability to sustain the same muscle force throughout the task duration. Apparently, the participants were not motivated enough to maintain the exact same force level possibly because they found it difficult to maintain the grip posture for 5 min, which was physically demanding.

3.4.5 Limitations of the study

This study did not consider variations caused by different grip force levels and hand-arm postures during task performance. Instead, the researcher instructed a sustained moderate grip force and allowed the participants to decide the posture that was the most comfortable for them. Moreover, young male adults who never had prior experience on long term vibration were recruited because the study wanted to determine the signs on the early stages of exposure among healthy individuals.

3.5 Conclusion

A 5-min exposure to handle vibration with sustained moderate grip force, represented by a constant submaximal ECR contraction, decreased the sensitivity of the middle finger and increased perceived discomfort on the hand and elbow. It also influenced the intention or ability of the participants to grip the handlebar in the required manner due to discomfort caused by vibration in the hand area, which led to a slightly low grip and muscle force generation.

Chapter 4. Effects of Two Forearm Postures and Grip Force Levels during Handle Vibration

4.1 Introduction

Musculoskeletal disorder is a type of occupational disease that needs more attention (Linaker & Walker-Bone, 2015). The wrist, elbow, shoulder, and neck are the common upper limb areas that are triggered by such work-related disorder (US DHHS NIOSH, 1997). Prevalent use of vibrating hand tools is one of the primary risk factors involved in acquiring such disorders (Bovenzi et al., 1987; Gemne & Saraste, 1987; van der Windt et al., 2000). Additionally, agricultural machineries and road construction equipment with high engine vibration also transmit excessive vibration to the hands and arms (Cutini et al., 2017; Layaoen et al., 2015; Revilla et al., 2015). In using these tools and equipment, sustained grip and various arm postures are typically required for proper handling and control (Pan et al., 2018). These differences in applied forces and postures can have added strain to the hand and forearm resulting to potentially higher risk of injuries and disorders. Besides muscle pain and discomfort, fundamental hand functions like grip strength can be reduced after long-term exposure (Gerhardsson & Hagberg, 2019), while finger sensitivity can be affected even after short-term exposure to handle vibration (presented in Chapter 3). These can lead to difficulty in performing simple work-related tasks such as tool handling and operation.

These disorders are primarily caused by too much exposure to handle vibration. Vibration signals are commonly analyzed using Fast Fourier Transform (FFT) wherein time-based signals are converted to frequency-based data. The relationship between the vibration level and the frequency range provides more meaningful information than what can be seen in vibration signals as a function of time. Vibration frequency spectrum shows frequency bands where peak vibration amplitudes occur and what causes them to happen. Moreover, vibration can be measured along three different axes, and this gives valuable information about the direction of the vibration source. The amount of transmitted vibration to the hand-arm area which is influenced by factors such as hand-arm posture, grip and push forces, external environment, and vibration direction (ISO 5349-1, 2001), likewise promulgates upper extremity injuries and diseases (Adewusi et al., 2010; Burström & Lundström, 1994; Cundiff, 1976). Vibration transmissibility is the ratio between the vibration acceleration on the desired measurement location and on the source.

Unlike single-handle vibration tools, dual-handle guided machines such as hand tractors, lawn mowers, and hydro tillers have two common handle structures: (1) bullhorn and (2) straight type bar (shown in Figure 4.1) that entail a neutral or pronated forearm posture. Several studies focused on determining and reducing HTV using a hand tractor that had a similar handle design as a bullhorn type bar (Binarao et al., 2017; Layaoen et al., 2015; Mojica et al., 2016; Revilla et al., 2015; Yap et al., 2016). Some research provided knowledge about vibration transmissibility on these two postures with extended (180°) or bent (90°) elbow (Adewusi et al., 2010; Aldien et al., 2005). However, in actual operations of dual-handle machineries, a 180° or 90° elbow angle is rarely applied. In addition, the grip level while handling these machineries can vary from mild to hard, depending on the task at hand. Mild grip is useful when the equipment only needs support for maneuvering, like for lawn mower where the grass yard has flat surface or hand tractor where the farm soil is soft. On the other hand, hard grip is common when the equipment must be fully controlled, like making a steep corner turn or cultivating an untilled farm soil. Generally, this type of dual-handle machineries mainly requires various grip force levels to handle and operate, unlike other powered equipment such as jackhammers, pneumatic hammers, and drillers that need additional downward forces during operation.

Hence, this study examined the influence of two forearm postures: (1) neutral and (2) pronated, with two grip forces: (1) mild and (2) hard, while maintaining a slightly bent elbow, during handle vibration. Specifically, it aims to determine the effects on the wrist and elbow transmitted vibration, activities of four forearm muscles namely the ECR, FF, FCU, and FCR, grip strength reduction, and perceived upper limb discomfort.

4.2 Methods

4.2.1 Participants

This study recruited 16 young male adults with a mean age, height, and weight of 23.3 ± 2.8 years, 173.2 ± 5.2 cm, and 64.0 ± 7.6 kg, respectively. The participants were all healthy individuals who have not been exposed to long-term handle vibration and have not had any serious injuries on their upper extremity. Each participant accomplished a written informed consent before the experiment. Furthermore, this study was approved by the Research Ethics Committee of the Faculty of Design in Kyushu University.

4.2.2 Vibration source

The signal source is a customized vibration table (Sinfonia Technology Co., LTD., Japan) with a nominal frequency of 60 Hz that was installed with a fabricated handlebar attachment frame. The attachment frame held the two handlebars in place as shown in Figure 4.1. The mean total vibration accelerations measured on the tip of the handlebars were 13.0 m/s^2 and 10.5 m/s^2, respectively. This was further discussed in section 4.2.5.

4.2.3 Experiment procedure

The objective and flow of the experiment were briefly explained to each participant. Basic information and measurements such as age, height, weight, handedness (Oldfield, 1971), pre-task maximum grip strength and pre-task subjective discomfort rating of the upper limb were requested from them. Surface EMG electrodes were placed on the forearm muscles and tri-axial accelerometers were tightly attached to the wrist and near the elbow joint. All nodes were attached on the dominant hand side of the participant.

Prior to the task performance, every participant was instructed to practice the required grip force level using a dynamometer that displayed grip force exertion. Once familiarized, the participant was asked to perform the task, which was to hold a vibrating handle with the required grip force for 5 min. He was then requested to maintain the same hand-arm posture, with an elbow and upper arm angles of 120°–160° and 10°–40° (shown in Figure 4.1). A monitor that showed the wrist extensor muscle activity was used to guide the participant in maintaining the required grip force for the entire exposure duration. Forearm muscle activities and vibration acceleration along the x-, y-, and z-axes were recorded during each task performance. Furthermore, post-task grip strength and subjective discomfort rating were also measured. Then, a 30-min seated rest was given before performing the next random condition. The entire experiment lasted for 3 h for each participant, including preparation, task performance, and rest period.

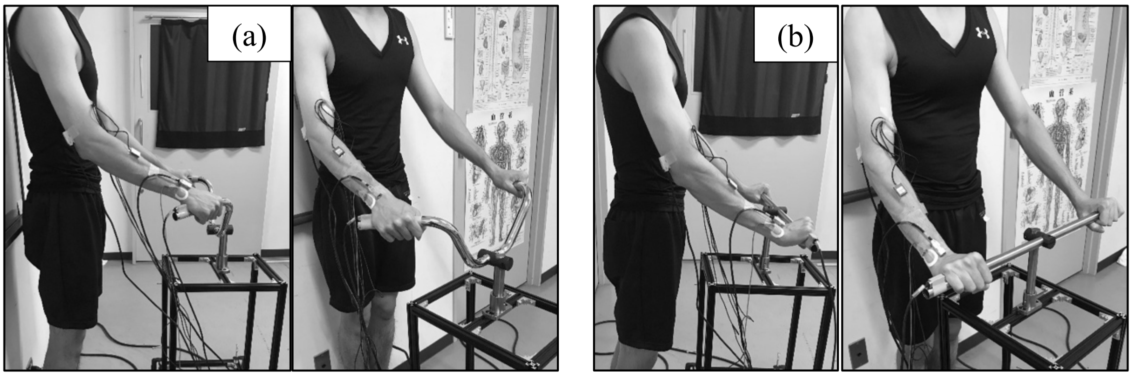

Figure 4.1. Experiment set-up of the second study: demonstration of a (a) neutral and (b) pronated forearm with elbow and upper arm angles of 120°–160° and 10°–40°.

4.2.4 Experiment design

The study followed a 2 × 2 repeated measures design wherein two forearm postures and grip force levels were examined. A bullhorn or straight handlebar was used to simulate neutral or pronated forearm. Furthermore, mild and hard grip force levels were approximately 10% and 50% of each participant's maximum grip strength. The four task conditions were designated as N_M–neutral forearm with mild grip, N_H–neutral forearm with hard grip, P_M–pronated forearm with mild grip, and P_H–pronated forearm with hard grip. A random task sequence was assigned to each participant for counterbalancing.

4.2.5 Measurements

Transmitted vibration

In this study, the vibration source was manufactured to have a nominal frequency of 60 Hz, which implied that peak amplitudes occurred in multiples of this frequency. From the vibration frequency spectra on the tip of the two handle structure prior to the task performance (shown in Figure 4.2), peak amplitudes along the x-, y-, and z-axes occurred within three major frequency bands: (1) 58~63, (2) 117~124, and (3) 177~182 Hz. The peak acceleration within these three bands along each axis ($Ax_{i\_j\_k}$, $Ay_{i\_j\_k}$, and $Az_{i\_j\_k}$) was used to calculate the total vibration acceleration, $AT_{i\_j\_k}$. This computation was performed in all the measurement locations in each task condition.

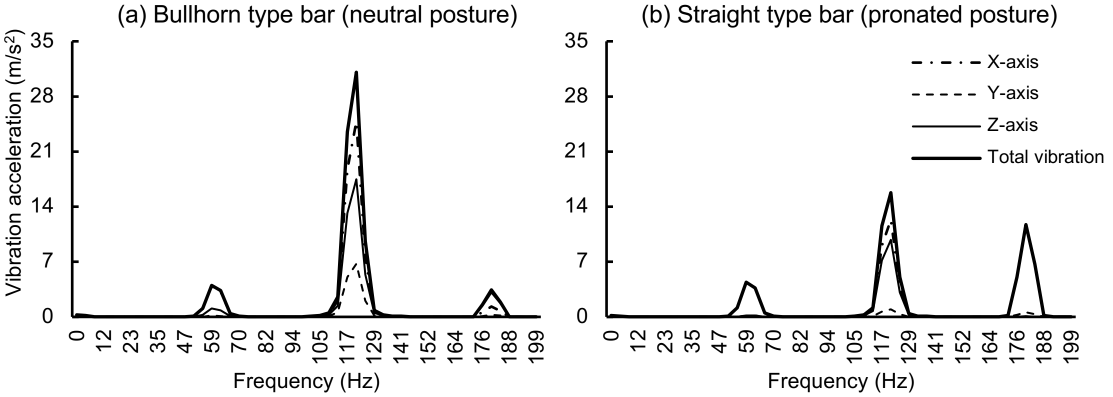

Figure 4.2. Frequency spectra of the baseline vibration value with peak accelerations present within three frequency bands: (1) 58~63, (2) 117~124, and (3) 177~182 Hz.

The total vibration accelerations on three locations: handle, wrist, and elbow were measured using a tri-axial accelerometer (Pico Technology, Japan). It was defined as:

$$AT_{i\_j\_k} = \sqrt{{Ax_{i\_j\_k}}^2 + {Ay_{i\_j\_k}}^2 + {Az_{i\_j\_k}}^2} \tag{4.1}$$

i = baseline, handle, wrist, elbow;
j = (1) 58~63, (2) 117~124, (3) 177~182 Hz;
$k = N_M, N_H, P_M, P_H$

where $AT_{i\_j\_k}$ is the total vibration acceleration, $Ax_{i\_j\_k}$ is the peak vibration acceleration measured along the x-axis, $Ay_{i\_j\_k}$ is the peak vibration acceleration measured along the y-axis, and $Az_{i\_j\_k}$ is the peak vibration acceleration measured along the z-axis within the frequency band (*j*) during each task condition (*k*).

Before every task, the total vibration acceleration on the handle ($AT_{baseline\_j\_k}$) was measured to serve as the reference baseline value. Then, the acceleration on the handle ($AT_{handle\_j\_k}$), wrist ($AT_{wrist\_j\_k}$), and elbow ($AT_{elbow\_j\_k}$) were simultaneously measured during each task condition. The ratio between the peak accelerations, within the major frequency bands, on various locations during the task and the reference baseline value prior to task performance was designated as the percentage of transmitted vibration to that specific location within the frequency spectra. It was calculated as:

$$Tr_{i\_j\_k} = \frac{AT_{i\_j\_k}}{AT_{baseline\_j\_k}} \, x \; 100 \qquad (4.2)$$

i = baseline, handle, wrist, elbow;
j = (1) 58~63, (2) 117~124, (3) 177~182 Hz;
k = N_M, N_H, P_M, P_H

where $Tr_{handle\_j\_k}$, $Tr_{wrist\_j\_k}$, and $Tr_{elbow\_j\_k}$ are the percentages of transmitted vibration to the handle, wrist, and elbow within the major frequency band (*j*) during each task condition (*k*).

The raw signal of vibration per axis was transmitted from the measurement location to ML880 PowerLab 16/30 (ADInstruments, New Zealand) at a sampling rate of 1 kHz. It was digitally filtered in LabChart 7.3.8 (ADInstruments, New Zealand) with a 350 Hz low pass since peak accelerations beyond 350 Hz were not observed, specifically during unfiltered baseline or pre-task vibration measurement. The chart view window of the software showed a time-based signal; hence, the raw waveform had to be converted to frequency-based using the Fast Fourier Transform (FFT) with FFT size of 512 and 50% overlap on Hann (cosine-bell) window. Frequency-based analysis is a more common method than time-based when analyzing vibration data because it shows where the peak amplitudes are normally present and what affects their deviation.

Grip strength reduction

Maximum grip strength was measured using a T.K.K.5710B Dynamometer (Takei, Japan), which was connected to a TSA-110 strain amplifier (Takei, Japan). Each participant was instructed to perform two trials of 5-s maximal grip using the dominant hand, separated by a 10-s rest. The participant was then asked to grip the handle of the dynamometer while standing with the arm closely tucked to the side of the trunk, elbow flexed at 90°, and forearm and hand in the neutral position. The researcher supported the opposite side of the dynamometer during the test to ensure that the measured value and muscle activities were not influenced by lifting. The average of the two trials was designated as the post-task grip strength and the percentage reduction was calculated in reference to the pre-task grip strength value.

Subjective discomfort rating

A scale from zero (no discomfort) to 10 (worst possible discomfort), illustrated by the Wong-Baker FACES rating scale was used to determine the perceived discomfort of every participant after each task condition. The assessment locations were the fingers, hand, forearm, elbow, upper arm, and shoulder of the dominant hand side.

Forearm muscle activity

The surface EMG placements, MVC measurements, and % MVC computations followed the same procedure discussed in Section 3.2.5 since the same forearm muscles namely the ECR, FF, FCU, and FCR were considered in this study.

Similarly, the MVC and actual activities of ECR, FF, FCU, and FCR were measured using the BA-U410m surface bipolar active EMG electrodes (Nihon Santeku, Japan) while a ground electrode was placed on the styloid process of the ulna. The EMG signal was amplified using a BA1104m bio-instrumentation amplifier (Nihon Santeku, Japan) before it was transmitted to ML880 PowerLab 16/30 (ADInstruments, New Zealand) at a sampling rate of 1 kHz. Then, the signal was digitally filtered in LabChart

7.3.8 (ADInstruments, New Zealand) with a 10–350 Hz band pass to eliminate noise signals (Conrad & Marklin, 2014; Kong & Lowe, 2005a). Lastly, the normalized muscle activity or % MVC was used for comparison.

4.2.6 Statistical analysis

Two-way repeated measures ANOVA was used to test the influence of forearm posture and grip force level on grip strength reduction. Meanwhile, three-way repeated measures ANOVA was used to determine the influence of forearm posture, grip force level, and vibration exposure time on the forearm muscle activities and transmitted vibration. The Greenhouse-Geisser correction was applied when the data violated the assumption of sphericity, while the Bonferroni correction was accounted for multiple comparisons. Lastly, subjective discomfort rating was assessed using the Wilcoxon signed-rank test, specifically: (1) N_M vs. N_H, (2) N_M vs. P_M, (3) N_H vs. P_H, and (4) P_M vs. P_H. Partial eta squared was included to indicate the effect size. The SPSS Statistics 25.0 (IBM, USA) was used in all the statistical tests.

4.3 Results

4.3.1 Transmitted vibration

Total vibration acceleration measured on the handle, wrist, and elbow

The total vibration accelerations ($AT_{i\_j\_k}$) were calculated using Eq. (4.1). Peak accelerations measured on the handle, wrist, and elbow during task performance of five randomly selected participants were presented in Figures 4.3, 4.4, and 4.5. The figures illustrate how vibration signals oscillated on various frequencies, essentially on three major frequency bands while holding the handlebars on two different postures and grip force levels.

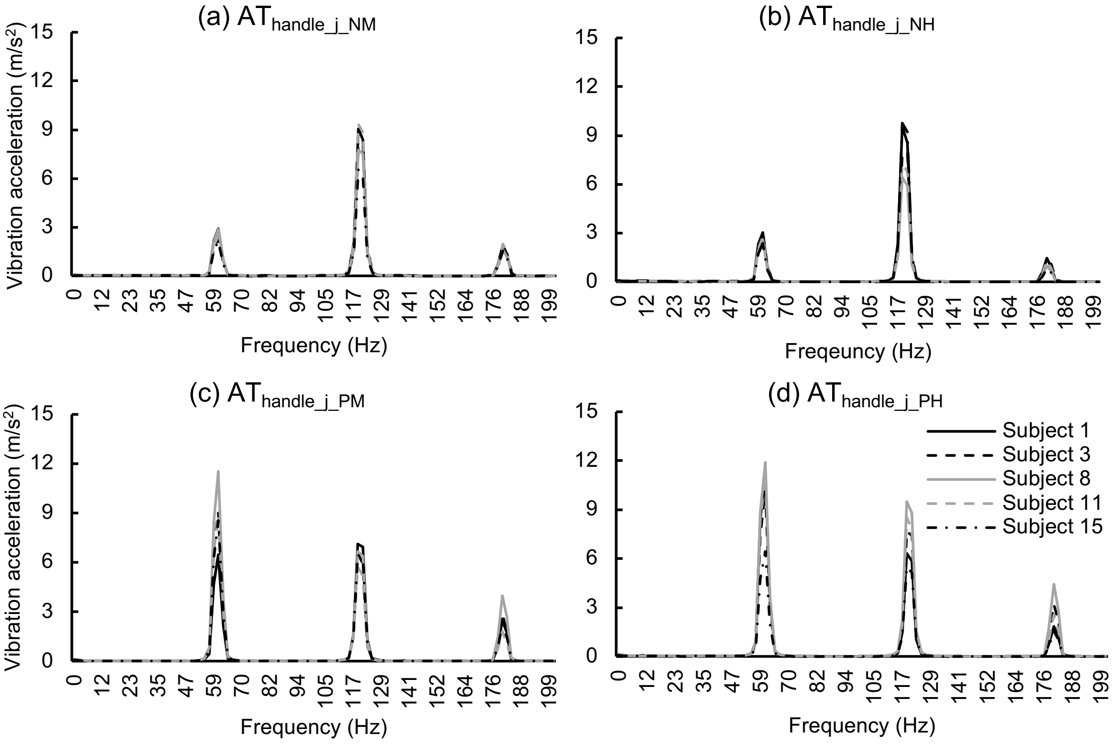

Figure 4.3. Frequency spectra of the total vibration acceleration measured on the handle.

Note: $AT_{handle\_j\_k}$ = total vibration acceleration on the handle, within frequency band *j*, during *k* condition, where *j* = (1) 58~63, (2) 117~124, and (3) 177~182 Hz and *k* = $N_{M/H}$ or neutral posture with mild/hard grip and $P_{M/H}$ or pronated posture with mild/hard grip.

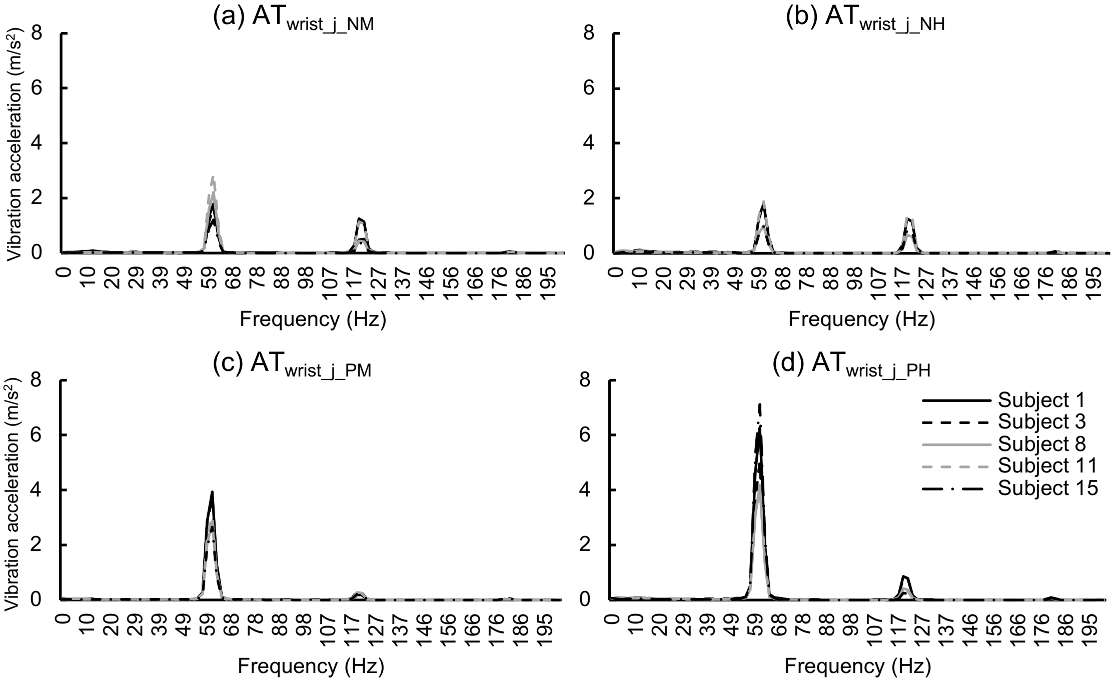

Figure 4.4. Frequency spectra of the total vibration acceleration measured on the wrist.

Note: $AT_{wrist\_j\_k}$ = total vibration acceleration on the wrist, within frequency band *j*, during *k* condition, where *j* = (1) 58~63, (2) 117~124, and (3) 177~182 Hz and *k* = N$_{M/H}$ or neutral posture with mild/hard grip and P$_{M/H}$ or pronated posture with mild/hard grip.

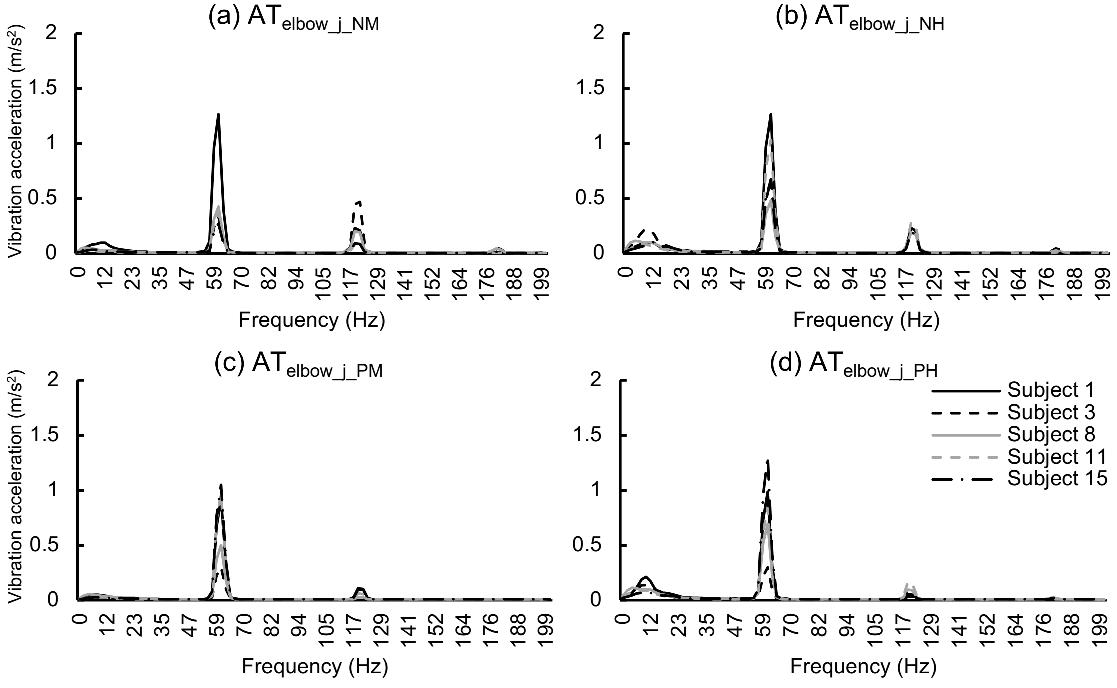

Figure 4.5. Frequency spectra of the total vibration acceleration measured on the elbow.

Note: $AT_{elbow\_j\_k}$ = total vibration acceleration on the elbow, within frequency band *j*, during *k* condition, where *j* = (1) 58~63, (2) 117~124, and (3) 177~182 Hz and *k* = N$_{M/H}$ or neutral posture with mild/hard grip and P$_{M/H}$ or pronated posture with mild/hard grip.

The peak total vibration accelerations on the frequency spectra shown in Figures 4.3, 4.4, and 4.5 were common to all the participants. Table 4.1 summarizes the mean total vibration acceleration prior to task performance and during each task condition of all the 16 subjects.

Table 4.1. Average peak total vibration acceleration (in m/s^2) measured at baseline and on the handle, wrist, and elbow of 16 participants within the three major frequency bands.

Condition	$AT_{baseline\_j\_k}$			$AT_{handle\_j\_k}$			$AT_{wrist\_j\_k}$			$AT_{elbow\_j\_k}$		
(*k*)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
N_M	3.9	32.0	3.2	2.5	8.7	1.9	1.8	0.5	0.0	0.3	0.1	0.0
N_H	4.1	32.2	3.1	2.9	8.4	1.6	1.9	1.0	0.1	0.7	0.2	0.0
P_M	7.5	14.2	10.0	8.7	7.2	3.1	2.9	0.2	0.0	0.5	0.1	0.0
P_H	7.6	14.6	9.8	9.8	7.4	2.5	4.6	0.6	0.1	0.7	0.1	0.0

Note: $AT_{baseline\_j\_k}$ = total vibration acceleration prior to task performance; $AT_{i\_j\_k}$ = total vibration acceleration on location (*i* = handle, wrist, elbow), where *j* = (1) 58~63, (2) 117~124, and (3) 177~182 Hz and *k* = $N_{M/H}$ or neutral posture with mild/hard grip and $P_{M/H}$ or pronated posture with mild/hard grip.

Vibration transmitted to each measurement location

The percentage of transmitted vibration to the handle, wrist, and elbow, within the major frequency bands (*j* = (1), (2), and (3)), during the four task conditions (*k* = N_M, N_H, P_M, and P_H) were calculated using Eq. (4.2) and they are summarized in Table 4.2.

Table 4.2. Mean percentage of vibration transmitted to various measurement locations.

Condition	$Tr_{handle\_j\_k}$			$Tr_{wrist\_j\_k}$			$Tr_{elbow\_j\_k}$			Mean *TR*		
(*k*)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	Handle	Wrist	Elbow
N_M	62	27	60	46	2	1	6	0	1	50	16	2
N_H	71	26	52	46	3	2	17	1	1	50	17	6
P_M	116	51	31	38	2	0	6	0	0	66	13	2
P_H	128	50	26	60	4	1	9	1	0	68	22	3

Note: $Tr_{i\_j\_k}$ = vibration transmitted to location (*i* = handle, wrist, elbow); Mean *TR* = mean transmissibility of the three frequency bands on each location, where *j* = (1) 58~63, (2) 117~124, and (3) 177~182 Hz and *k* = $N_{M/H}$ or neutral posture with mild/hard grip and $P_{M/H}$ or pronated posture with mild/hard grip.

Graphically, the average transmissibility from the source to the handle, wrist, and elbow showed a decreasing trend (shown in Figure 4.6). In addition, three-way ANOVA revealed that transmitted vibration was influenced by measurement location ($F(1.253,17.538) = 476.399$, $p < 0.001$, $\eta^2 = 0.971$), forearm posture ($F(1,14) = 18.080$, $p = 0.001$, $\eta^2 = 0.564$), and grip force level ($F(1,14) = 8.110$, $p = 0.013$, $\eta^2 = 0.367$).

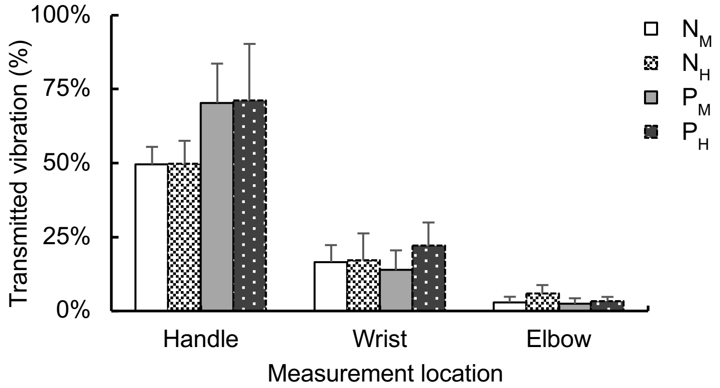

Figure 4.6. Illustration of the mean percentage of vibration transmitted to various measurement locations during each task condition.

Note: $N_{M/H}$ = neutral posture with mild/hard grip; $P_{M/H}$ = pronated posture with mild/hard grip.

Mean transmissibility to the wrist and elbow

Wrist: The vibration transmitted to the wrist was significantly influenced by grip force ($F(1,14) = 5.515$, $p = 0.034$, $\eta^2 = 0.283$), but not by forearm posture and vibration exposure time. Moreover, there was also a statistically significant interaction between the effects of: (1) posture and grip force ($F(1,14) = 12.028$, $p = 0.004$, $\eta^2 = 0.462$) and (2) grip force and exposure time ($F(4,56) = 7.204$, $p = 0.001$, $\eta^2 = 0.340$) on the vibration transmitted to the wrist. In Figure 4.7 (a), transmissibility on pronated posture was significantly higher on hard grip than mild grip (p = 0.018), while transmissibility on neutral posture did not differ between hard and mild grips. Hard grip also resulted to a decreasing transmissibility through the 5-min exposure, while mild grip had a consistent transmissibility trend. One outlier data for WVT was removed.

Elbow: The vibration transmitted to the elbow was influenced by posture ($F(1,15) = 16.801$, $p = 0.001$, $\eta^2 = 0.528$), grip force ($F(1,15) = 16.104$, $p = 0.001$, $\eta^2 = 0.518$), and exposure time ($F(1.730,25.943) = 5.519$, $p = 0.013$, $\eta^2 = 0.269$). There was a significant interaction between the effects of: (1) posture and grip force ($F(1,15) = 7.048$, $p = 0.018$, $\eta^2 = 0.320$) and (2) grip force and exposure time ($F(1.849,27.736) = 3.880$, $p = 0.036$, $\eta^2 = 0.206$) on the vibration transmitted to the elbow. Specifically, hard grip on neutral posture led to a significantly higher transmissibility than the other three conditions, which did not differ from each other. Additionally, hard grip led to a decreasing transmissibility, while mild grip had a consistent transmissibility trend (shown in Figure 4.7 (b)).

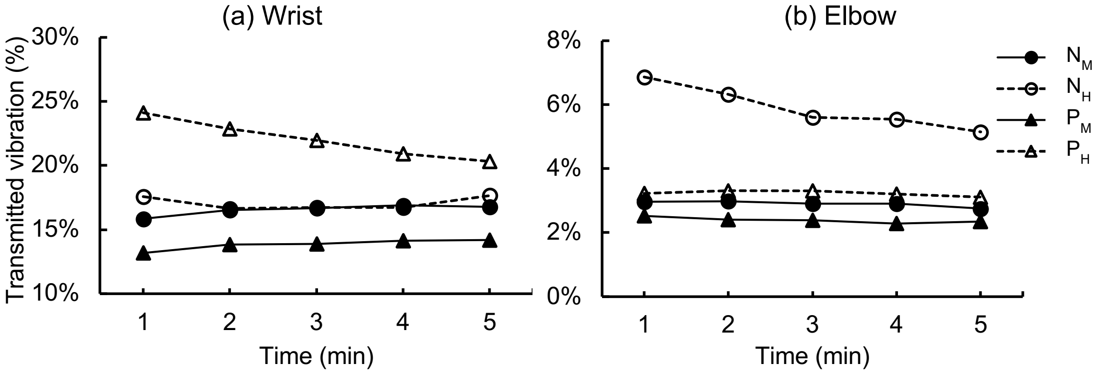

Figure 4.7. A time plot of the mean percentage of vibration transmitted to the (a) wrist and (b) elbow during a 5-min handle vibration exposure.

Note: $N_{M/H}$ = neutral posture with mild/hard grip; $P_{M/H}$ = pronated posture with mild/hard grip.

4.3.2 Grip strength reduction

Grip strength (in kgf) was reduced after performing all conditions (pre-task = 39.4 ± 5.8; N_M = 34.3 ± 6.2; N_H = 28.5 ± 6.3; P_M = 33.9 ± 6.3; P_H = 26.1 ± 6.7). Two-way repeated measures ANOVA showed that the mean reduction (in %) was significantly influenced by grip force level ($F(1,15) = 55.243$, $p < 0.001$, $\eta^2 = 0.786$), but not by forearm posture. Further analysis showed that hard grip led to yield significantly higher mean reductions than mild grip, on both postures (shown in Figure 4.8).

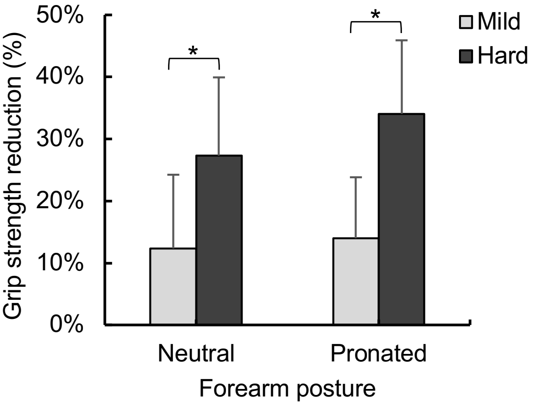

Figure 4.8. Mean percentage of grip strength reduction after performing each condition (* $p < 0.05$).

4.3.3 Subjective discomfort rating

Subjective discomfort ratings were significantly higher ($p < 0.01$) on hard grip than mild grip on both forearm postures (shown in Figure 4.9). Moderate to severe discomfort was perceived on the fingers, hand, and forearm after hard grip and mild to moderate after mild grip. Additionally, there were significantly higher perceived discomforts on the elbow ($Z = -2.228, p = 0.026$), upper arm ($Z = -2.046, p = 0.041$), and shoulder ($Z = -2.030, p = 0.042$) after hard grip on pronated than neutral posture.

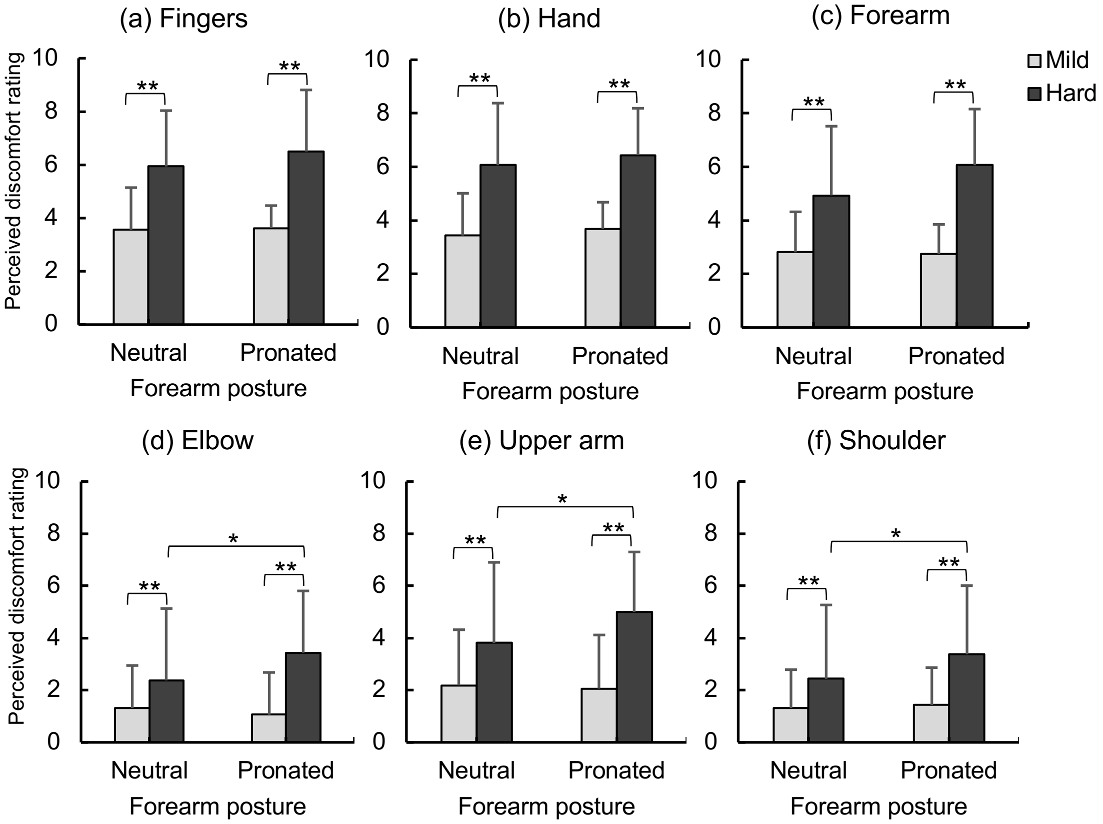

Figure 4.9. Mean subjective discomfort ratings on the upper limb after performing each condition (** $p < 0.01$; * $p < 0.05$; n = 16).

4.3.4 Forearm muscle activities

Mean ECR activity

The activity of the ECR was used to represent the required grip level for the 5-min handle vibration. Its activity was monitored and displayed to guide the participants in sustaining their grip force at the required level. Essentially, this study characterized grip force exertion using the ECR activity, which was benchmarked from the method used in Chapter 3 of this dissertation.

Three-way ANOVA revealed that ECR activity was influenced by forearm posture ($F(1,15) = 12.928, p = 0.003, \eta^2 = 0.463$) and grip force level ($F(1,15) = 104.028$, $p < 0.001$, $\eta^2 = 0.874$), but not by vibration exposure time. The test also showed a significant interaction between the effects of posture and grip force on ECR activity ($F(1,15) = 5.888, p = 0.028, \eta^2 = 0.282$). In Figure 4.10, neutral posture had a significantly higher muscle activity than pronated posture during hard grip ($p = 0.014$), while there was no significant difference during mild grip. Lastly, ECR activities for the entire 5 min were consistent indicating that the required grip levels were sustained accordingly.

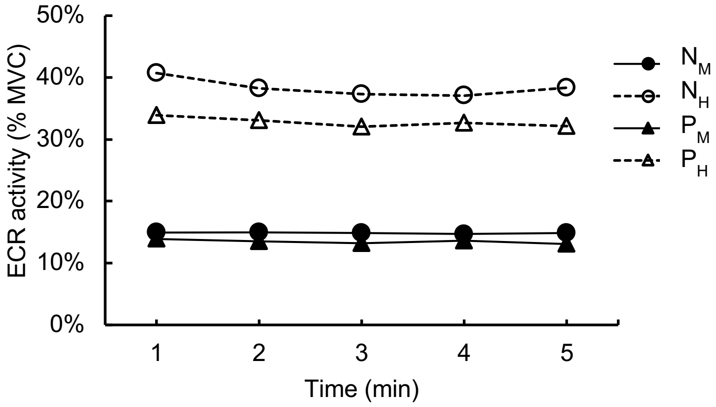

Figure 4.10. A time plot of ECR activity on each condition during a 5-min handle vibration exposure.

Note: $N_{M/H}$ = neutral posture with mild/hard grip; $P_{M/H}$ = pronated posture with mild/hard grip.

Mean activities of FF, FCU, and FCR

Three-way ANOVA revealed that the mean activity of FF ($F(1,12) = 54.459$, $p < 0.001$, $\eta^2 = 0.819$), FCU ($F(1,9) = 27$, $p = 0.001$, $\eta^2 = 0.750$), and FCR ($F(1,9) = 91.014$, $p < 0.001$, $\eta^2 = 0.910$) were influenced by grip force level but not by forearm posture and vibration exposure time. Essentially, hard grip led to significantly higher forearm muscle activities than mild grip, on both postures. The statistical test also revealed an interaction bordering on significance between the effects of posture and exposure time on FF activity ($F(2.754,33.054) = 2.453$, $p = 0.085$, $\eta^2 = 0.170$), grip force and exposure time on FCU activity ($F(1,4) = 2.189$, $p = 0.090$, $\eta^2 = 0.196$), and posture, grip force, and exposure time on FCR ($F(4,36) = 2.192$, $p = 0.089$, $\eta^2 = 0.196$). Several outlier data for FF, FCU, and FCR activities were removed.

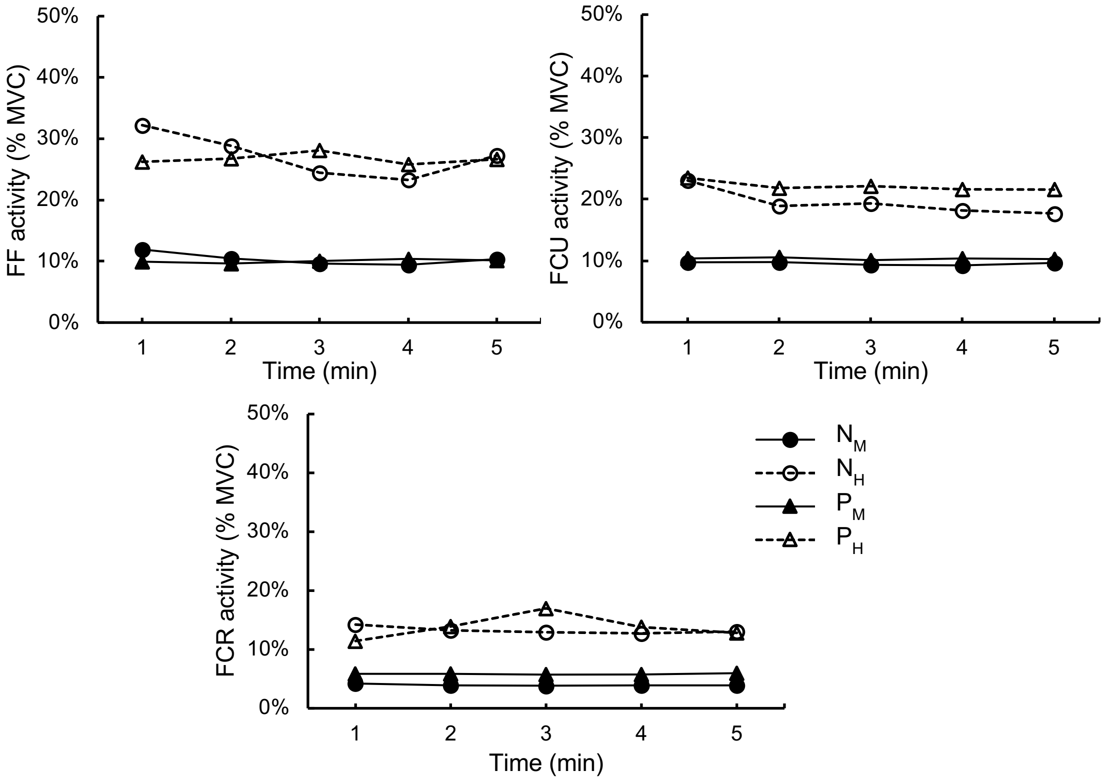

Figure 4.11. A time plot of forearm muscle activities on each condition during a 5-min handle vibration exposure.

Note: $N_{M/H}$ = neutral posture with mild/hard grip; $P_{M/H}$ = pronated posture with mild/hard grip.

4.4 Discussion

The effects of handle vibration were amplified by biomechanical factors such as forearm posture and grip force level, which directly affects transmissibility (Adewusi et al., 2010). Musculoskeletal disorders along the upper extremity are some of the common occupational diseases related to vibration exposure and body posture. This study found how two common forearm postures and grip force levels, applied when operating dual-handle vibration equipment, influenced wrist and elbow transmitted vibration, forearm muscle contractions, grip force reduction, and upper limb discomfort.

4.4.1 Influence of resonant frequency, grip force level, and forearm posture on the vibration transmitted to the wrist and elbow

Like any solid structure, the amount of vibration transmitted to a body location decreases as the frequency increases and the location gets farther away from the source (Adewusi et al., 2010). Vibration signal is dissipated along the muscles and tissues, which both served as bone dampers. This was evident in this study, where the vibration transmitted to the handle, wrist, and elbow had a decreasing trend (shown in Figure 4.6). It was reported that vibration attenuated along the tissues closest to the joints, such as the wrist and elbow, while less attenuation occurred across the joints (Reynolds & Angevine, 1977). Transmissibility also depends on resonant frequencies of the vibration source such that frequencies below 100 Hz could be transmitted to the forearm, those below 40 Hz could be transmitted to the upper arm (Pyykko et al., 1976), and frequencies above 200 Hz were concentrated to the hands (Aatola, 1989; Pyykko et al., 1976; Reynolds & Angevine, 1977). Additionally, magnitudes of transmitted vibration along the forearm and upper arm at frequencies below 200 Hz are affected by different grip force levels (Adewusi et al., 2010). Hence, with major frequency components: (1) 58~63, (2) 117~124, and (3) 177~182 Hz that were present in this study, the significant influence of grip force on the vibration transmitted to the wrist and elbow was further explained. Transmissibility was found to be higher on hard grip than mild grip because as force exertion increases, both the stiffness of the arm and effective mass of the palm and hand likewise increase (Pan et al., 2018), making vibration flow easily along the upper limb.

Meanwhile, the influence of forearm posture was evident on the vibration transmitted to the wrist and elbow, specifically during hard grip. Wrist transmissibility was significantly higher on pronated forearm than neutral forearm (shown in Figure 4.7 (a)), which can be explained by the relationship between the grip ability and the forearm posture. A vast majority of research stated that a pronated forearm yields lower grip strength than neutral or supinated forearm (Fan et al., 2019; Mogk & Keir, 2003; Murugan et al., 2013; Richards et al., 1996) because of the unnatural position of FF and other related muscles during pronated posture (Brand & Hollister, 1993). Theoretically, higher grip exertion leads to higher transmissibility. However, in this study, although neutral posture was able to maintain a significantly higher hard grip force than pronated posture, the latter had the higher wrist transmissibility. A strong possibility was that the wrist, where the accelerometer was placed, was in constant extension during pronation to help maintain the required hard grip and this created added stiffness to the accelerometer location, which in turn led to higher vibration transmissibility. In addition, it was reported that, during grip strength test, the common self-selected wrist posture was 35° extension and 7° ulnar deviation, thereby creating the maximum grip strength among other assigned postures (O’Driscoll et al., 1992).

On the other hand, elbow transmissibility was significantly higher on neutral forearm than pronated forearm during hard grip. This might be because the upper arm was closely tucked into the side of the trunk during the former posture, making the elbow joint stiffer while it was slacker on the latter posture. Although, there were very few studies discussing the difference on transmitted vibration to the upper arm area during different forearm postures, there were several that focused on the effects of bent and extended elbow combined with various grip and push forces (Adewusi et al., 2010; Aldien et al., 2005). Essentially, the influence of grip force on the vibration transmitted to the elbow were more pronounced in the bent-arm posture which was attributed to the stiffening of muscles, tissues, and joints that tend to affect the dampening of the hand-arm system (Adewusi et al., 2010).

4.4.2 Potential effects of forearm posture, grip force level, and vibration exposure time on upper limb fatigue

Effects on grip strength reduction

Grip strength is a basic measurement in determining musculoskeletal health and disorder (Amaral et al., 2019). This parameter identifies not just the upper limb muscle weakness, but also the overall individual strength (Bohannon, 2012). When the upper extremity is subjected to a high level of physical workload, a reduction on grip strength is typically observed (Rashid et al., 2018; Widia & Dawal, 2011). In this study, higher grip strength reduction was observed after hard grip than mild grip, indicating that sustained hard grip caused fatigue to the hand-arm system resulting to force reduction. The highest reduction, which was 34.1 ± 11.9%, was calculated after performing sustained hard grip on pronated forearm posture (P_H) and this was closely followed by performance of hard grip on neutral posture (N_H) with a reduction of 27.3 ± 12.6%. Lastly, the reductions calculated during mild grip on both postures were $N_M = 12.3 \pm 11.9\%$ and $P_M = 14.0 \pm 9.8\%$. Meanwhile, this study failed to show any significant influence of forearm posture on grip force reduction.

Effects on perceived discomfort on the upper limb

Subjective discomfort on the upper extremity was rated and compared to determine the level of workload and difficulty of each experimental condition. Moderate to severe discomfort was perceived on the fingers, hand, and forearm after hard grip than mild grip, on both forearm postures, indicating that sustained force exertion caused extreme discomfort and possibly fatigue on the distal arm. Additionally, perceived discomfort on the elbow, upper arm, and shoulder were significantly higher on hard grip (moderate rating) than mild grip (mild rating), while the influence of forearm posture was significant during hard grip. Subjective discomfort on the elbow, upper arm, and shoulder were higher after P_H (pronated forearm) than N_H (neutral forearm). Since the proximal arm muscles, including the biceps brachii, brachialis, and brachioradialis, are also involved when changing forearm posture (Güleçyüz et al., 2017; Naito et al., 1995), this could possibly explain why perceived discomfort varied between the two postures. An electromyographic study confirmed that the brachialis and brachioradialis activities increased during a slow supination to pronation movement, indicating a clear contraction gain during forearm pronation (Naito et al., 1994). Considering the involvement of these muscles on pronation, combining that with high grip exertion, this could have intensified the stress perceived by the proximal arm.

Effects on forearm muscle activities during the 5-min vibration exposure

Repetitive and long duration tasks that require extreme muscle work can lead to chronic pain and fatigue causing serious musculoskeletal disorders (Allen et al., 2008; Rota et al., 2014). The behavior of muscle contractions, specifically the % MVC of a specific muscle of interest during such stressful conditions, is a common way to assess the stress and strain that the muscle undergoes. In this study, the % MVC of forearm muscles namely the ECR, FF, FCU, and FCR were analyzed to determine the influence of forearm posture, grip force level, and vibration exposure duration on the hand-arm system. Generally, changes in forearm posture affect the length of the extrinsic hand muscles, which are determinants of hand strength and stamina (Motamed, 1982; Tubiana, 1981). Power or hard grip involves the long flexor and extensor muscles of the fingers and thumb that run along the wrist, forearm, and elbow. Since every muscle has an optimal length where it can produce maximum contraction, external changes that can shorten or lengthen the muscle fibers can decrease its optimal response (Brand & Hollister, 1993; Norkin & Levangie, 1992). Essentially, this supported the effects on forearm muscle activities found in this study.

ECR activity: The muscle contraction of the wrist extensor represented the required grip force level (mild and hard) during task performance. It was displayed in a television monitor to guide each participant on the real-time grip exertion and it was required to be consistent throughout the 5-min vibration exposure that is why it was not influenced by exposure duration. However, it was significantly affected by grip force level and forearm posture. Although each participant was instructed to exert the same force on hard grip or mild grip on both postures, ECR contraction, specifically on hard grip, was higher on neutral posture than pronated posture (shown in Figure 4.10). This implied that it was difficult to consistently grip hardly on pronated posture than neutral posture because of the unnatural position of the forearm during the former. This coincided with the findings on perceived discomfort, wherein higher discomfort was perceived on the proximal arm during hard grip on pronated forearm than neutral forearm.

FF, FCU, and FCR activities: For these muscles, the % MVC on hard grip were significantly higher than mild grip on both postures. Generally, higher force exertion leads to higher muscle activities, which can be harmful if continuously performed for a long period. The interaction between the effects of posture and grip force on the % MVC of these muscles was not observed, but weak interactions between posture or grip force and exposure time were present. The muscle activity of FF as a function of vibration exposure time varied between neutral and pronated forearm posture. FF activity had a decreasing trend on neutral posture, while it had a consistent trend on pronated posture. FF was activated during finger flexion and it can yield the least contraction on pronated forearm because the flexor muscles wrap around the radius during pronation (Brand & Hollister, 1993; Richards et al., 1996). This could explain why the neutral posture produced a higher mean activity than pronated posture, in which the flexor muscle was lengthened and could not optimally contract. Secondly, the muscle activity of FCU, which was responsible for ulnar and radial deviation of the wrist, as a function of time varied between hard and mild grip. FCU activity had a decreasing trend on hard grip while it had a consistent trend on mild grip. This was because muscle forces are specifically higher during the initial stages of maximal contraction, in which the required number of motor units are the highest, and then gradually decrease throughout the remaining duration (Hoffman et al., 2009; Löscher et al., 1996). Lastly, the FCR muscle activity had a three-way interaction among posture, grip force, and exposure time wherein neutral posture on both grip force level had a decreasing trend, while pronated posture on both grip force level had an increasing trend. FCR was activated during wrist flexion and the difference in wrist range of motion on both postures was evident during the last minutes of vibration exposure. Specifically, the wrist was engaged more during pronated posture to provide added force to meet the required grip level resulting to higher muscle force exertion.

4.4.3 Implications of integrating handle vibration, intense force exertion, and awkward posture

The significant findings in this study were seen on the combined effects of consistently gripping hard on pronated forearm during handle vibration. It initially transpired on the higher vibration transmitted to the wrist, which might have contributed to the difficulty in sustaining the required grip level on this posture. Since hard grip made the wrist stiffer, vibrations could easily flow and dissipate along the forearm muscles, which could gradually reduce as they reach the elbow joint. Considering the vibration transmitted to the lower arm, the unnatural posture of the forearm, which caused the FF muscles to lengthen further, resulted to sub-optimal grip exertion. Finally, the perceived discomfort on the upper limb, specifically on the elbow, upper arm, and shoulder intensified the immediate effects and potential risks of this condition.

4.4.4 Limitations of the study

This study mainly focused on static posture and sustained grip exertion to establish the exclusive effects of these two biomechanical factors when subjected to HAV. Dynamic movements such as pushing downward, lifting, or maneuvering the handle, which could also influence the effects of transmitted vibration to the hand and arm were not considered. Although these movements are normally accompanied with hard grip force, other muscles are also involved when doing these motions that can also stimulate fatigue development. Nevertheless, future research regarding dynamic movements involved in handling other powered equipment should also be conducted while the findings in this study can be helpful to further characterize their effects.

4.5 Conclusion

With constant handle vibration and exposure time, hard grip force influenced higher vibration transmitted to the wrist and elbow, higher % MVC of the forearm muscles, higher grip strength reduction, and moderate to severe discomfort on the fingers, hand, and forearm. Meanwhile, the effects of forearm posture showed its significance precisely during hard grip. Pronated forearm posture influenced higher vibration transmitted to the wrist, lower % MVC of FF as a function of vibration exposure time, and higher perceived discomfort on the elbow, upper arm, and shoulder.

Chapter 5. Effects of Various Handle Shapes and Surface Profiles during Vibration Exposure

5.1 Introduction

Long-term exposure to HAV can lead to neurological, vascular, and musculoskeletal disorders, which manifest in the hands, fingers, elbows, and shoulders (Krajnak et al., 2015; Milosevic & McConville, 2012). Aside from external stressors such as vibration, prolonged hard grip and awkward hand-arm posture were strongly linked to many upper extremity musculoskeletal disorders such as reduced grip strength and increased upper limb discomfort (US DHHS NIOSH, 1997). These issues primarily stimulated the need to prevent or limit handle vibration exposure. However, basic hand tools and equipment were gradually converted to mechanized ones to increase the productivity and efficiency of industrial and service firms. Consequently, these mechanized tools generate vibration, which are transmitted to humans.

Various interventions were made to minimize the harmful effects of HTV. Handle grip designs were standardized specially for ease and comfort of hand tool usage. The Canadian Center for Occupational Health and Safety (CCOHS) described some major ergonomic concerns about hand tools like weight, shape, diameter, length, separation between handles (for pliers and tongs), materials, and textures. CCOHS also stated that for powered hand tools that generate vibration, the primary way to reduce transmissibility is during the tool design stage. On the other hand, for machineries and equipment that have not been designed properly on the initial stages of development, reactive measures that include the usage of various types of grip straps (Binarao et al., 2017; Layaoen et al., 2015), installation of motorcycle or bicycle handle grips (Layaoen et al., 2015; Yap et al., 2016), and utilization of anti-vibration gloves (Hewitt et al., 2014; ISO 10819, 2013) were implemented.

During the design phase, handle size seemed to be the most explored factor of handle grips. Majority of studies investigated various diameters, from 20 mm to 60 mm (Dusenberry et al., 2008; Edgren et al., 2004; Kong & Lowe, 2005b) and tested how grip strength and tool manipulation were influenced by various sizes. Small diameter handle was found to be more difficult to grip than large handle because of too much flexion the FF had to be subjected to, however it was more appropriate if tasks required speed and dexterity (Cochran & Riley, 1983). On the other hand, large diameter handle which gave more surface area in contact with the hand, could disable the user in providing a stronger and more controlled grip of the handle (Amis, 1987; Kong & Lowe, 2005b). Consequently, most studies agreed that the optimal handle diameter was around 30 mm to 40 mm wherein most users can grip the handle without exerting too much effort and still have enough control of the equipment (Kong & Lowe, 2005b; Yakou et al., 1997).

Several studies also considered varying the handle shapes for better grip and torque generation (McDowell et al., 2012; Rossi et al., 2014; Seo & Armstrong, 2011). The palmar and handle surface contact varies with the handle contour. Larger surface contact led to higher torque generation (Seo & Armstrong, 2011) and the difference in handle contour influenced various forearm muscle coordination, specifically during maximal grip exertion (Rossi et al., 2014). Handle surface profile is another design factor that contribute to grip comfortability and ease of usage. There were limited studies discussing the effects of texture on the ability to grip hardly. In one study, it was found that texture seemed to influence perceived force exertion during precision grip. It explained that a smooth surface was perceived to give greater force exertion than what was truly applied, and the opposite was observed for a rough surface (Flanagan & Wing, 1997). Besides its effects on strength, surface profile was also a factor for grip comfort and ease. It provides the magnitude of palmar and handle grip friction, which is associated with the ability to grasp the handle without slipping or dropping accidentally. As opposed to handle size, there have been very limited studies providing the cumulative effects of various handle shapes and surface profiles especially during extreme conditions such as constant handle vibration, sustained grip force, and awkward forearm posture.

Chapter 4 investigated two forearm postures: semi-neutral and pronated with two grip force levels: mild and hard, which are common when using dual-handle vibrating machineries. It was found that consistent hard grip led to higher vibration transmitted to the wrist and elbow while hard grip on pronated forearm resulted to higher muscle force exertion, higher grip force reduction, and higher upper arm discomfort, than strongly gripping on a neutral forearm or mildly gripping on either posture. Since the former study did not implement any handle grip, this study intends to determine the impact of various designs during pre-imposed extreme conditions. While a poor handle design can aggravate the effects of HAV and can stimulate early development of musculoskeletal disorders; a good design may limit unnecessary grip exertion, promote grip comfort, and reduce vibration transmission.

This study aimed to investigate the influence of various handle grip designs specifically on the harmful effects of constant handle vibration, sustained moderate grip exertion, and pronated forearm posture. The primary focus is to determine the effects of using a handle grip and how three handle shapes: circular, double-frustum, and elliptic with two surface profiles: smooth and patterned affect hand and wrist transmitted vibration, grip strength reduction, finger sensitivity, subjective discomfort along the upper limb, grip comfort perception, perceived strength of vibration, and forearm muscle activities. The secondary goal is to assess which handle design has the least harmful effects on the hand-arm system.

5.2 Methods

5.2.1 Participants

This study recruited 14 young male adults with a mean age, height, and weight of 24.3 ± 3.1 years, 173.8 ± 4.8 cm, and 67.3 ± 8.2 kg, respectively. All participants were right-hand dominant based on the Edinburgh Handedness Inventory test (Oldfield, 1971). The primary inclusion criteria were individuals who have not been exposed to long-term handle vibration and have not had any serious injuries on their upper extremity. Each participant accomplished a written informed consent before participating in the experiment. Furthermore, this study was approved by the Research Ethics Committee of the Faculty of Design in Kyushu University.

5.2.2 Vibration source

A customized vibration table (Sinfonia Technology Co., LTD., Japan) that has a nominal frequency of 60 Hz was used as the vibration source. It was installed with a fabricated handlebar attachment frame, which held a straight bar type handle structure in place (shown in Figure 5.1 (a)). The grip diameter and length of the handle structure was 20 mm and 600 mm, respectively. The mean pre-task vibration acceleration measured on the tip of the handlebar was 11.45 ± 0.81 m/s^2.

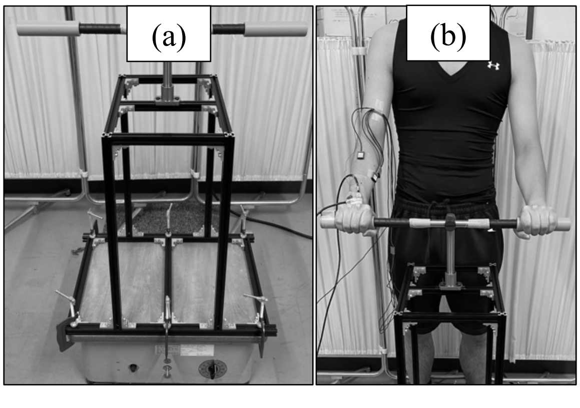

Figure 5.1. Experiment set-up of the third study: (a) vibration source and (b) hand-arm posture during task performance.

5.2.3 Handle grip designs

Six handle grips, with three different shapes: circular, double-frustum, and elliptic, and two surface profiles: smooth and patterned were designed in Fusion 360 (Autodesk, USA) and printed using a Creality CR-10S Pro 3D printer (Creality, China) with Polylite PLA filament (Polymaker, China). The image and design measurements are presented in Figure 5.2 and Table 5.1.

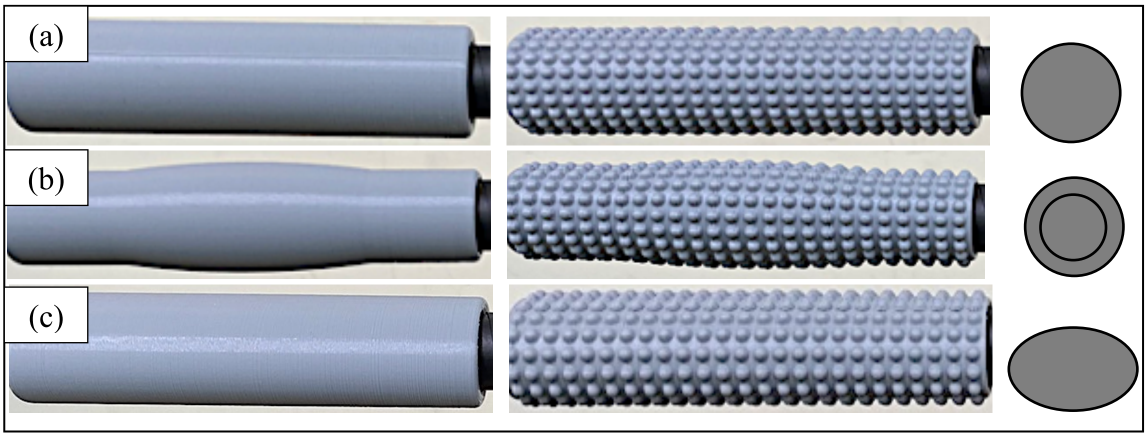

Figure 5.2. Illustration of smooth and patterned surface profile for: (a) circular, (b) double-frustum, and (c) elliptic-shaped handles.

Table 5.1. Dimensions (in mm) of the handle grip designs examined in this study.

Diameter	Circular		Double-frustum		Elliptic	
	Smooth	Patterned	Smooth	Patterned	Smooth	Patterned
Inner	22.4	22.4	22.4	22.4	22.4	22.4
Outer$_1$	33.0	30.0	28.0	26.5	28.0	25.0
Outer$_2$	N/A	N/A	33.0	30.0	35.0	31.0

Note: Outer$_1$ and Outer$_2$ for double-frustum = outer diameter of edge and middle; Outer$_1$ and Outer$_2$ for elliptic = crosswise and lengthwise outer diameter; For the dimensions of the rounded spike on patterned surface profile: height = 2 mm; center distances = 5 mm; diameter = 3 mm (filleted).

5.2.4 Experiment procedure

The goal and task flow of the experiment were briefly explained to each participant. Basic information such as age, handedness, and subjective discomfort rating of the upper limb; and fundamental physical measurements like height, weight, maximum grip strength, and finger sensitivity were taken prior to task performance. Afterwards, surface EMG electrodes were put on the forearm muscles and tri-axial accelerometers were attached on the dorsal aspect of the hand and wrist of the dominant hand side.

After preparation, each participant was instructed to practice the required grip level, which he needed to sustain for the entire 2-min task duration. A monitor, which displayed the activity of the wrist extensor muscle (ECR), was placed in front of the participant to guide him in maintaining the requested grip exertion. This was benchmarked from the method applied in Chapter 3 of this dissertation, in which the ECR activity was used to represent the grip force level. Once familiar with the required force, the participant was instructed to hold the vibrating handle (shown in Figure 5.1 (b)) with moderate grip (30% of his maximum grip strength) and pronated forearm with an elbow and upper arm angle of 140°–160° and 20°–40°. The tip of the handle was inserted with different handle grips for each experiment condition. Each condition was performed for 2 min and a 10-min seated rest was given afterwards. Forearm muscle activities and vibration acceleration were recorded during task performance while maximum grip strength, finger sensitivity, subjective discomfort rating, grip comfort rating, and perceived vibration rating were measured after each task. The entire experiment lasted for 2.5 h for each participant, including preparation, task performance, and rest period.

5.2.5 Experiment design

The experiment design was a 3 × 2 repeated measures in which three handle grip shapes and two surface profiles were investigated. Another task condition, without handle grip, was added in the experiment to verify the effects of implementing a handle grip. Overall, there were seven experiment conditions designated as NG–no handle grip, C_S–circular-smooth, D_S–double-frustum-smooth, E_S–elliptic-smooth, C_P–circular-patterned, D_P–double-frustum-patterned, and E_P–elliptic-patterned. A random task sequence was assigned to each participant for counterbalancing.

5.2.6 Measurements

Transmitted vibration

The vibration source used in this study had a nominal frequency of 60 Hz, which suggested that peak amplitudes occur in multiples of this frequency. The vibration frequency spectrum (shown in Figure 5.3) measured on the tip of the handlebar prior to task performance confirmed that peak amplitudes along the x-, y-, and z-axes were within three frequency bands, which were multiples of the nominal frequency: (1) 58~63, (2) 117~124, and (3) 177~182 Hz. The peak acceleration within these three bands along each axis ($Ax_{i\_j\_k}$, $Ay_{i\_j\_k}$, and $Az_{i\_j\_k}$) were used to calculate the total vibration acceleration, $AT_{i\_j\_k}$. This computation was done in all the measurement locations, including tip of the handle, dorsal aspect of the hand, and wrist, in each task condition.

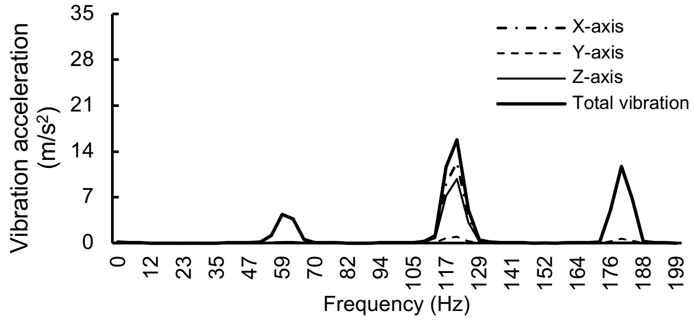

Figure 5.3. Baseline vibration frequency spectrum with peak accelerations present within three major frequency bands: (1) 58~63, (2) 117~124, and (3) 177~182 Hz.

The total vibration acceleration on each measurement location was measured using a tri-axial accelerometer (Pico Technology, Japan). It was computed as:

$$AT_{i\_j\_k} = \sqrt{{Ax_{i\_j\_k}}^2 + {Ay_{i\_j\_k}}^2 + {Az_{i\_j\_k}}^2} \qquad (5.1)$$

i = baseline, hand, wrist;
j = (1) 58~63, (2) 117~124, (3) 177~182 Hz;
$k = NG, C_S, D_S, E_S, C_P, D_P, E_P$

where $AT_{i\_j\_k}$ is the total vibration acceleration and $Ax_{i\_j\_k}$, $Ay_{i\_j\_k}$, and $Az_{i\_j\_k}$ are the peak vibration accelerations along the x-, y-, and z-axes in the frequency band (*j*) during each task condition (*k*).

Prior to task performance, the total vibration acceleration on the handle ($A_{T\_baseline}$) was measured to serve as the baseline value for computing the vibration transmitted to the hand and wrist within each frequency band and during each experiment condition. This was defined as:

$$Tr_{i\_j\_k} = \frac{AT_{i\_j\_k}}{AT_{baseline\_j\_k}} x\ 100 \qquad (5.2)$$

i = *hand, wrist;*
j = *(1) 58~63, (2) 117~124, (3) 177~182 Hz;*
$k = NG, C_S, D_S, E_S, C_P, D_P, E_P$

where $Tr_{hand\_j\_k}$ and $Tr_{wrist\_j\_k}$ are the percentage of transmitted vibrations to the hand and wrist within the major frequency band (*j*) during each task condition (*k*).

The raw signal was transmitted at a sampling rate of 1 kHz to ML880 PowerLab 16/30 (ADInstruments, New Zealand) and it was digitally filtered in LabChart 7.3.8 (ADInstruments, New Zealand) with a 350 Hz low pass. The time-based waveform was converted to frequency-based data using Fast Fourier Transform (FFT) with FFT size of 1,024 and 50% overlap on Hann (cosine-bell) window.

Grip strength reduction

Pre-task and post-task maximum grip strength were measured using a T.K.K.5710b Dynamometer (Takei, Japan) which was connected to a TSA-110 strain amplifier (Takei, Japan). The protocol was to perform two trials of 5-s maximum grip using the dominant hand, which was separated by 10 s of rest. Each participant was instructed to hold the Takei dynamometer while standing with the arm closely tucked to the side of the trunk, elbow flexed at 90°, and forearm and wrist in neutral position. The opposite side of the dynamometer was supported by the researcher during the test to ensure that the maximum exertion will not be influenced by lifting. The average of the two trials were calculated and this was used to compute for the percentage reduction.

Finger sensitivity

Finger sensitivity was quantified using the two-point discrimination test with Touch Test® Two-Point Discriminator (Exacta Precision & Performance, China). Every participant was asked to close the eyes, lend the dominant hand to the researcher, position the arm in supination, and determine whether one or two points (which was being prodded by the researcher using the two-point disk) were perceived by each finger. The fingers were selected one by one and was poked randomly by either one or two points (with a point distance starting from 2 mm) for at least seven times. If the participant determined the correct number of pinpoints for at least four of the seven trials, the researcher could proceed to the next finger. Else, the researcher stayed on the same finger and gradually increased the two-point distance (e. g. 2 mm to 3 mm and so on) until the participant could consistently state the correct number of pinpoints. The minimum distance that was consistently determined was recorded. Generally, sensitivity decreased when the minimum perceived distance increased from the pre-task value, otherwise it improved.

Subjective discomfort rating

A scale from zero (no discomfort) to 10 (worst possible discomfort), illustrated by the Wong-Baker FACES rating was used to determine the perceived discomfort after each task condition. The assessment locations were the fingers, hand, forearm, elbow, upper arm, and shoulder of the dominant hand side.

Grip comfort rating

Grip comfort was assessed through rating the perceived comfortability when gripping a specific handle grip design for the 2-min vibration exposure. A scale from zero (least comfortable) to 10 (extremely comfortable) was used to quantify comfort rating.

Perceived vibration level

Perceived level of vibration when using each handle grip design was rated from zero (imperceptible) to 10 (very strong) after each experiment condition was performed.

Forearm muscle activity

The MVC and actual activities of ECR, FF, FCU, and FCR were measured using the BA-U410m surface bipolar active EMG electrodes (Nihon Santeku, Japan) while a ground electrode was placed on the styloid process of the ulna. The EMG signal was amplified using a BA1104m bio-instrumentation amplifier (Nihon Santeku, Japan) before it was transmitted to ML880 PowerLab 16/30 (ADInstruments, New Zealand) at a sampling rate of 1 kHz and recorded in LabChart 7.3.8 (ADInstruments, New Zealand) with a 10–350 Hz band pass filter to eliminate noise signals (Conrad & Marklin, 2014; Kong & Lowe, 2005a). Lastly, the normalized muscle activity or % MVC was used for comparison. The surface EMG placements, MVC measurements, and % MVC computations followed the same procedure discussed in Section 3.2.5.

5.2.7 Statistical analysis

Paired t-test was used to determine the difference between no handle grip and with handle grip on transmitted vibration, grip strength reduction, and forearm muscle activities. Wilcoxon signed-rank test was used to assess the difference on two-point discrimination and subjective ratings between the two conditions.

Two-way repeated measures ANOVA was used to determine the influence of handle shape and surface profile on transmitted vibration, grip strength reduction, and forearm muscle activities. The Greenhouse-Geisser correction was applied when the data violated the assumption of sphericity, while the Bonferroni correction was accounted for multiple comparisons. Meanwhile, the Friedman test was used to assess the influence of handle shape and surface profile on two-point discrimination, subjective discomfort rating, grip comfort rating, and perceived vibration rating and the Wilcoxon signed-rank test for non-parametric pairwise comparison. Partial eta squared was included to indicate the effect size. The SPSS Statistics 25.0 (IBM, USA) was used in all the statistical tests.

5.3 Results

The results were analyzed into two parts, the effects of using a handle grip and the influence of handle shape and surface profile on transmitted vibration, grip strength reduction, finger sensitivity, subjective discomfort rating along the upper extremity, grip comfort, perceived strength of vibration, and forearm muscle activities. The effects of implementing a handle grip were assessed by comparing the no handle grip condition and with circular handle grip (C_S) condition on all the above-mentioned parameters. Afterwards, the influence of handle shape and surface profile on the same parameters was presented.

5.3.1 Transmitted vibration

Total vibration acceleration measured on the handle, hand, and wrist

The peak total vibration acceleration in the frequency band (*j*) on condition (*k*) were computed using Eq. (5.1). The calculated mean values are presented in Table 5.2.

Table 5.2. Average peak total vibration acceleration (in m/s^2) measured at baseline and on the hand and wrist of 14 participants within the three major frequency bands.

Condition (*k*)	$AT_{baseline\_j\_k}$			$AT_{hand\_j\_k}$			$AT_{wrist\_j\_k}$		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
NG	7.0	19.3	8.1	11.2	6.3	0.5	4.2	0.4	0.0
C_S	10.2	32.2	1.8	8.9	4.8	0.4	4.1	0.4	0.0
D_S	8.9	43.8	0.7	10.2	5.0	0.4	4.2	0.3	0.0
E_S	9.0	41.8	1.0	11.9	5.1	0.5	4.8	0.3	0.0
C_P	10.5	39.5	1.3	10.4	5.0	0.4	4.7	0.4	0.0
D_P	7.6	47.9	1.3	10.5	4.8	0.5	4.5	0.3	0.0
E_P	8.7	44.9	1.1	12.1	4.8	0.5	4.3	0.3	0.0

Note: $AT_{baseline\_j\_k}$ = total vibration acceleration on the handle prior to task performance; $AT_{i\_j\_k}$ = total vibration acceleration on location *(i = hand, wrist)*, where *j* = (1) 58~63, (2) 117~124, and (3) 177~182 Hz and *k* = NG or no handle grip, $C_{S/P}$ or circular-smooth/patterned, $D_{S/P}$ or double-frustum-smooth/patterned, and $E_{S/P}$ or elliptic-smooth/patterned.

Vibration transmitted to the hand and wrist

The percentage of vibration transmitted to the hand and wrist were computed using Eq. (5.2). The calculated values are shown in Table 5.3.

Table 5.3. Mean percentage of vibration transmitted to the hand and wrist.

Condition	$Tr_{hand\_j\_k}$			$Tr_{wrist\_j\_k}$			Mean *Tr*	
(*k*)	(1)	(2)	(3)	(1)	(2)	(3)	Hand	Wrist
NG	161	33	7	60	2	0	67	21
C_S	92	15	21	41	1	1	43	14
D_S	120	11	76	48	1	7	69	18
E_S	142	12	51	57	1	5	69	21
C_P	101	13	38	45	1	3	50	16
D_P	152	10	38	67	1	3	66	23
E_P	146	11	49	52	1	3	68	19

Note: $Tr_{i\_j\_k}$ = vibration transmitted to location *(i = hand, wrist)*; Mean *Tr* = mean transmissibility of the three frequency bands on each location, where *j* = (1) 58~63, (2) 117~124, and (3) 177~182 Hz and *k* = NG or no handle grip, $C_{S/P}$ or circular-smooth/patterned, $D_{S/P}$ or double-frustum-smooth/patterned, and $E_{S/P}$ or elliptic-smooth/patterned.

Paired t-test revealed that the vibration transmitted to the dorsal part of the hand ($t(10) = 6.732$, $p < 0.001$) and wrist ($t(9) = 3.308$, $p = 0.009$) were significantly higher during the no handle grip condition than the with handle grip (shown in Figure 5.4 (a)).

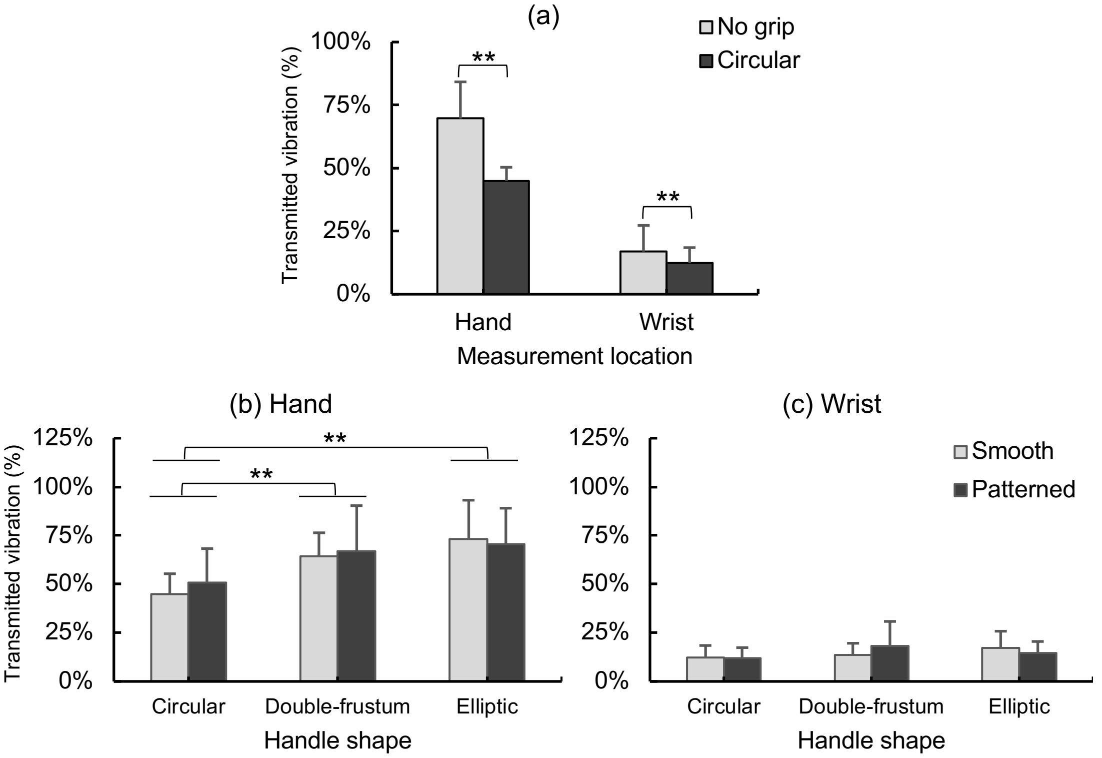

Figure 5.4. Illustration of the mean percentage of vibration transmitted to the hand and wrist: (a) comparison between none and with circular-shaped handle and (b) - (c) effect of various shapes and surface profiles (** $p < 0.01$).

Subsequently, two-way ANOVA showed that HTV was significantly influenced by handle shape ($F(2,20) = 14.215$, $p < 0.001$, $\eta^2 = 0.587$) but not by surface profile. In Figure 5.4 (b), HTV on circular grips were significantly lower than double-frustum ($p = 0.009$) and elliptic ($p < 0.001$) grips. In contrast, the test did not show any significant main effect of handle shape or surface profile on the vibration transmitted to the wrist (WTV) (shown in Figure 5.4 (c)). Several outlier data for HTV and WTV were removed.

5.3.2 Grip strength reduction

With the mean baseline grip strength of 40.3 ± 4.7 kgf, paired t-test revealed that the reduction between the no handle grip and with circular handle grip had no significant difference ($p = 0.131$). On the other hand, a clear trend on grip strength reduction showed that it was influenced by handle shape ($F(2,20) = 3.155$, $p = 0.064$, $\eta^2 = 0.240$) but not by surface profile. Essentially, elliptic-shaped handles had higher grip strength reduction than double-frustum handles (shown in Figure 5.5).

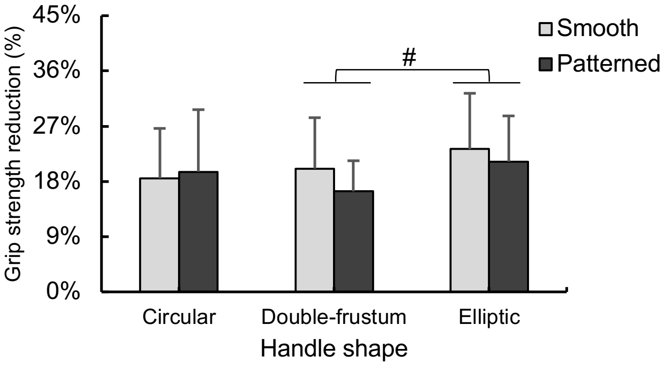

Figure 5.5. Mean percentage of grip strength reduction on various handle shapes and surface profiles ($^{\#}\, p < 0.10$).

5.3.3 Two-point discrimination test for finger sensitivity

Wilcoxon signed-rank test did not show any significant difference between the no handle grip and with circular handle grip condition on finger sensitivity (shown in Figure 5.6 (a)). Meanwhile, Friedman test revealed that surface profile significantly influenced the ring ($X^2(5) = 10$, $p = 0.075$) and small finger sensitivity ($X^2(5) = 9.834$, $p = 0.080$). Essentially, elliptic handle indicated a lower ring and small finger sensitivity on patterned than smooth surface ($Z = -2.121$, $p = 0.034$) (shown in Figures 5.6 (b) and 5.6 (c)).

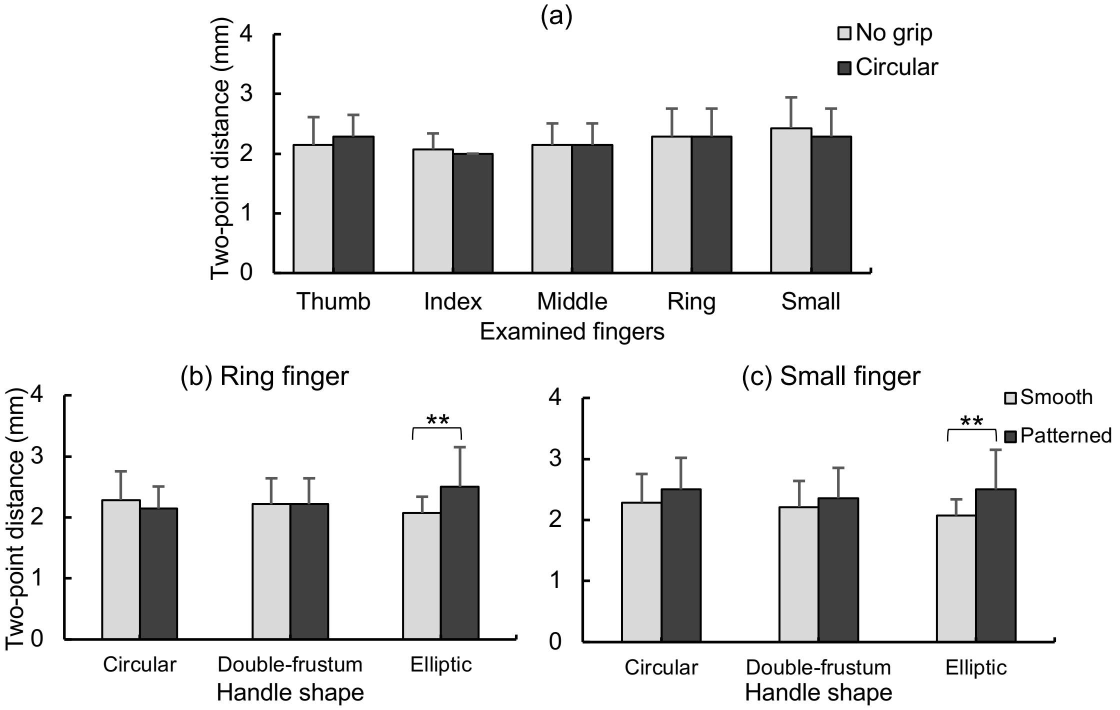

Figure 5.6. Mean perceived two-point distance on various shapes and surface profiles: (a) comparison between none and with circular-shaped handle and effect on the (b) ring finger and (c) small finger sensitivity (** $p < 0.01$; n = 14).

5.3.4 Subjective ratings

Discomfort rating on the upper extremity

A clear trend in subjective discomfort rating on the fingers ($Z = -1.702$, $p = 0.089$), forearm ($Z = -2.496$, $p = 0.013$), and shoulder ($Z = -1.667$, $p = 0.096$) between no handle grip and with circular handle grip condition indicated higher ratings after NG task (shown in Figure 5.7 (a)). Meanwhile, Friedman test revealed that handle shape and surface profile affected perceived discomfort on the fingers ($X^2(5) = 14.222$, $p = 0.014$) and hand ($X^2(5) = 16.063$, $p = 0.007$). Subsequent assessment using Wilcoxon signed-rank test showed that a higher discomfort on the fingers and hand was perceived after patterned than smooth surface on circular and elliptic shape (shown in Figures 5.7 (b) and 5.7 (c)).

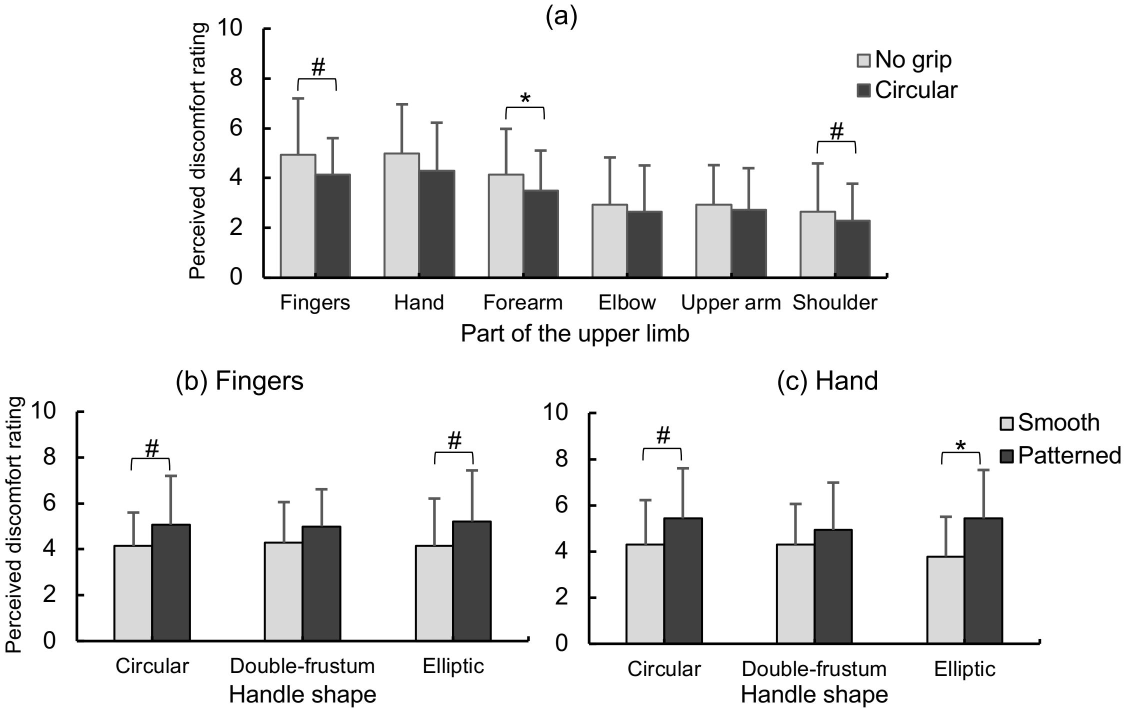

Figure 5.7. Mean subjective discomfort ratings on various shapes and surface profiles: (a) comparison between none and with circular-shaped handle and effect on the (b) fingers and (c) hand perceived discomfort ($* p < 0.05$; $^{\#} p < 0.10$; n = 14).

Grip comfort rating

Perceived grip comfort was significantly higher ($Z = -3$, $p = 0.003$) when circular handle grip was implemented than the no handle grip condition (shown in Figure 5.8 (a)).

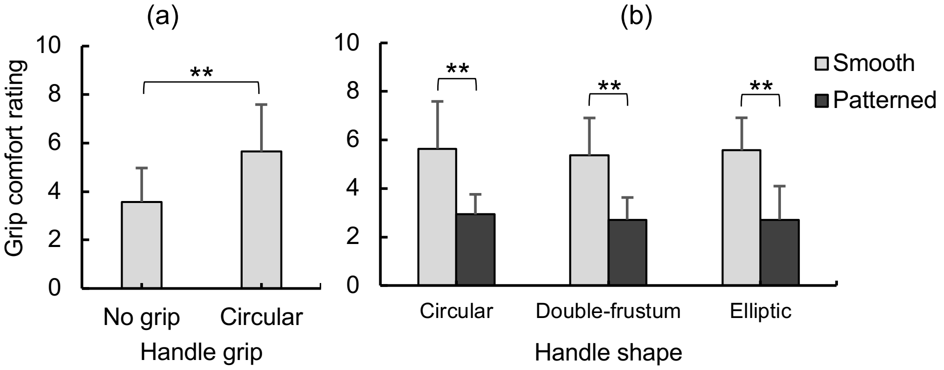

Figure 5.8. Mean grip comfort rating: (a) comparison between none and with circular-shaped handle and (b) effect of various shapes and surface profiles ($** p < 0.01$; n = 14).

Wilcoxon signed-rank test showed that surface profile significantly influenced grip comfort ($C_{S/P}$: $Z = -3.099$, $p = 0.002$; $D_{S/P}$: $Z = -3.210$, $p = 0.001$; $E_{S/P}$: $Z = -3.152$, $p = 0.002$), specifically smooth surface led to moderate comfort while patterned surface had least to slight comfort. However, the test did not show any significant effect of handle shape on grip comfortability (shown in Figure 5.8 (b)).

Perceived strength of vibration

Perceived strength of vibration was significantly higher ($Z = -2.358$, $p = 0.018$) when no handle grip was implemented. The mean rating during NG condition was 5.9 ± 1.9 or moderate strength while 4.6 ± 1.4 or little strength was perceived during C_S condition. On the other hand, Wilcoxon signed-rank test did not show any significant influence of handle shape and surface profile on the perceived strength of vibration. In all handle design conditions, there were little to moderate perceived strength.

5.3.5 Forearm muscle activities

Mean ECR activity

In this study, ECR activity was used to represent the required grip force level, which was 30% of maximum grip strength, during the 2-min handle vibration exposure. Essentially, ECR activity characterized the grip force exertion of the participants, which was benchmarked from the method applied in Chapter 3 of this dissertation.

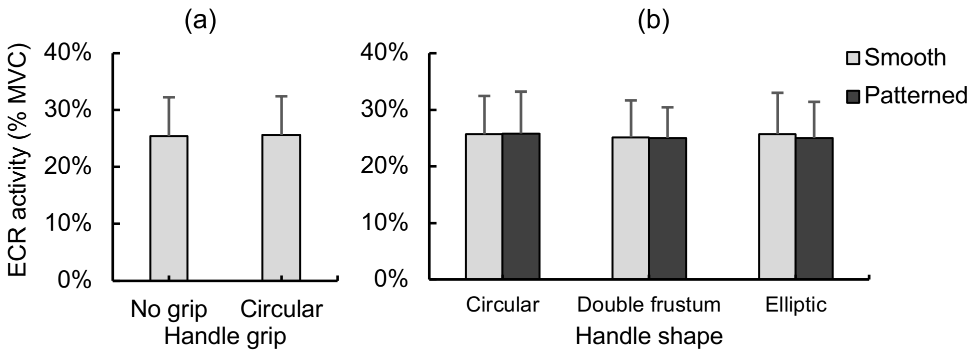

Figure 5.9. Mean ECR activity: (a) comparison between none and with circular-shaped handle and (b) effect of various shapes and surface profiles.

Paired t-test showed that ECR activity did not vary (*p* = 0.392) between no handle grip (25.3 ± 0.1%) and with handle grip (25.6 ± 0.1%). Similarly, two-way repeated measures ANOVA revealed that neither handle shape (*p* = 0.548) nor surface profile (*p* = 0.508) influenced the activity of this muscle (shown in Figure 5.9).

Mean activities of FF, FCU, and FCR

Paired t-test revealed no significant differences between no handle grip and with handle grip on FF (*p* = 0.127), FCU (*p* = 0.142), and FCR (*p* = 0.114) activities. In addition, two-way ANOVA did not indicate any significant influence of handle shape and surface profile on the activities of these forearm muscles (shown in Figure 5.10).

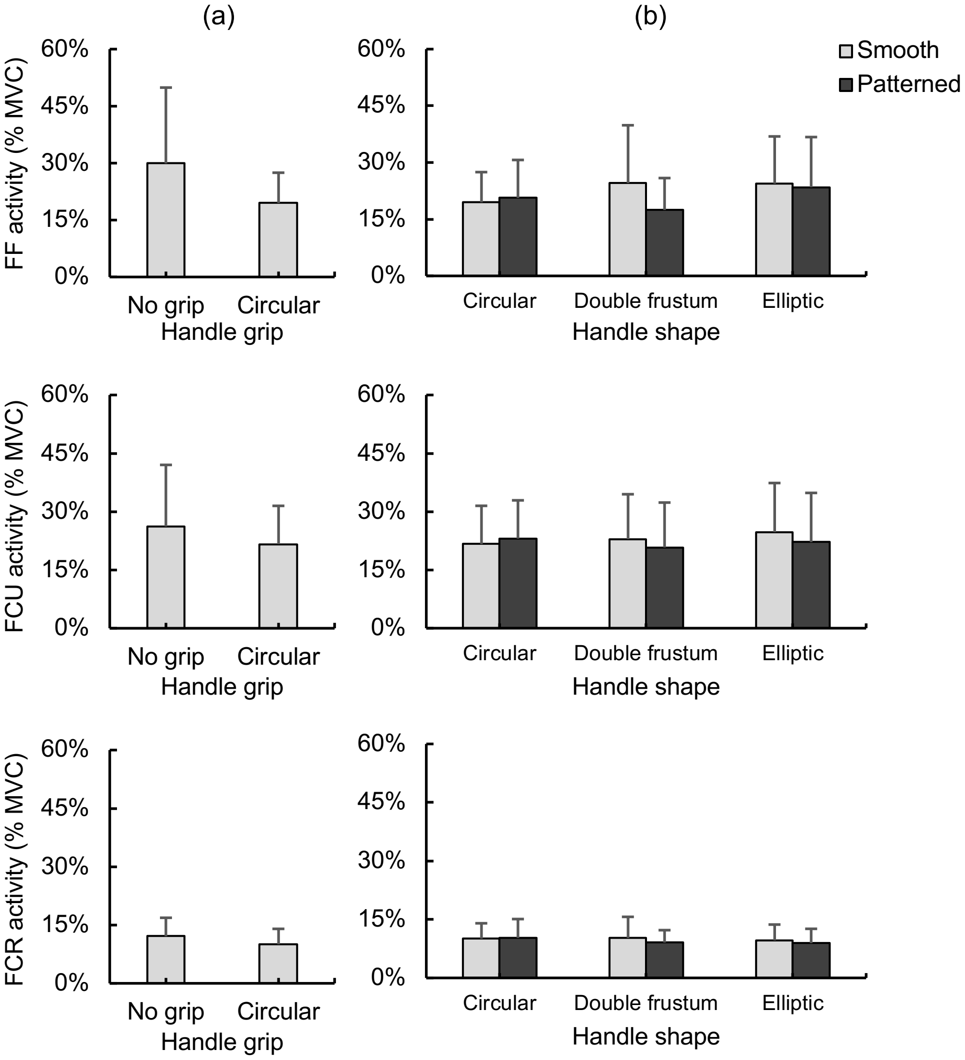

Figure 5.10. Mean forearm muscle activities: (a) comparison between none and with circular-shaped handle and (b) effect of various shapes and surface profiles.

5.4 Discussion

5.4.1 Effects of implementing a handle grip

The handlebar used in this study was a straight bar type with a grip diameter of 20 mm. This was benchmarked from the handle diameter of a hand tractor used in the study of Mojica et al. (2016), which is about 25 mm. This served as the no handle grip (NG) condition. The findings on NG was compared with the with handle grip or the C_S (circular and smooth handle) condition. This comparison showed how the presence of a regular circular handle grip affected transmitted vibration, muscle activity, fundamental hand parameters, and some subjective ratings. This study found that using a handle grip were significant on hand (HTV) and wrist (WTV) transmitted vibration, discomfort rating on the fingers, forearm, and shoulder, grip comfort, and perceived strength of vibration.

Essentially, C_S had lower HTV, WTV (shown in Figure 5.4 (a)), and perceived strength of vibration than NG which suggested that using a regular-sized handle grip reduced the tendency to absorb HAV. Although several studies linked high grip force level to high magnitude of transmitted vibration (Mann & Griffin, 1996; Marcotte et al., 2005), this study did not obtain a similar finding. Grip exertion on both handle grip conditions did not differ significantly, as seen on the forearm muscle activities especially ECR activity during NG and C_S (shown in Figures 5.9 (a) and 5.10 (a)) but transmitted vibration on both conditions was different. While the main distinction between NG and C_S was the handle grip diameter, wherein NG had a smaller grip size than C_S, another research supported that handle diameter did not influence the electrical activity of forearm muscles during gripping (Kong & Lowe, 2005b). In addition, since the required grip force in this study was moderate or about 30% of the maximum grip strength, forearm muscles only had submaximal contractions, which resulted to indistinctive differences between handle sizes. Hence, the difference in HTV, WTV, and perceived strength of vibration could not be related to grip exertion during task performance, as opposed to previous research (Mann & Griffin, 1996; Marcotte et al., 2005). Instead, the differences might be due to the proximity of the hand from the vibration source since having a handle grip provided additional layer of protection, which was about 6.5 mm, from the vibrating handle. Consequently, this led to significantly lower fingers, forearm, and shoulder discomfort and higher grip comfort.

Thus, implementing a handle grip during exposure to HAV, moderate grip exertion, and awkward forearm posture lessened HTV and WTV, minimized upper limb discomfort, and increased grip comfort as compared to using no handle grip. Given these findings, various handle shapes and surface profiles with closely similar diameters were investigated and the results were discussed in Sections 5.4.2 and 5.4.3.

5.4.2 Effects of handle shape

Hand transmitted vibration

HTV was significantly lower on circular grips than double-frustum and elliptic-shaped handles (shown in Figure 5.4 (b)). Generally, the task of moderately gripping various handle shapes for 2 min of handle vibration did not influence the ability to grip consistently, which was evident on the muscle activities of the ECR, FF, FCU, and FCR (shown in Figures 5.9 (b) and 5.10 (b)). However, previous research stated that finger force distribution and finger joint postures were affected by handle shapes (Rossi et al., 2014). In one instance, circular and double-frustum handles were found to generate the least total finger force during a screwing task (Kong et al., 2008). These might support why, in this study, HTV on circular handles were lower than either of the two other handle shapes even though grip forces across the three handle shapes did not vary significantly. Finger coordination was modified by the handle shape leading to uneven finger contact and force distribution. This could influence contact stiffness and grip stability and henceforth the transmitted vibration to the hands, since higher stiffness and stability could lead to higher transmissibility (Welcome et al., 2015).

Grip strength reduction

Grip strength reduction was lower after using double-frustum than elliptic handles (shown in Figure 5.5). Similar to one study, elliptic-shaped handles exhibited the least maximal grip force than either circular or double-frustum probably due to the differences in musculotendon parameters such as muscle length and moment arms which were altered by the handle shape (Rossi et al., 2014). The palm and handle contact area were greater on elliptic-shaped handles than on circular and double-frustum. Hence, larger palm area was under contact stress wherein soft tissues in the palm are compressed between the metacarpal and the vibrating handle. Although this experiment only required moderate grip exertion, transmitted vibration due to contact stress was able to propagate on the soft tissues of the palm, which caused temporary loss of finger sensitivity. Finger tactile acuity is essential to dexterous hand functions such as fine hand movements, gripping, and object manipulation (Zatsiorsky & Latash, 2004). This might have led to grip strength reduction found in this study. Meanwhile, handle sizes and task variations like static forceful grip or dynamic forceful grip should also be investigated, together with handle shape, since one research found that elliptic-shaped handles led to higher grip exertion than circular grips (Seo & Armstrong, 2011).

5.4.3 Effects of handle surface profile

Ring and small finger sensitivity

The ring and small finger sensitivity were influenced by surface profile. Essentially, both fingers perceived larger two-point distance on elliptic-shaped handle with patterned surface (E_P) than smooth surface (E_S). This implied that E_P elicited lower ring and small finger sensitivity than E_S. Tactile afferents that innervate the hand convey signals to the brain when the hand interacts with objects. This provides information such as the physical characteristics of the object and the contact perception between the object and the hand (Johansson & Flanagan, 2009). Besides the actual grip contact, various handle surface profiles that provide different frictional condition, could give stability and steadiness to the level of grip exertion (Cadoret & Smith, 1996; Flanagan & Wing, 1995; Johansson & Westling, 1984). Previous studies suggested that local frictional conditions could modify grip exertion at individual digits (Birznieks et al., 1998; Edin et al., 1992; Quaney & Cole, 2004). Generally, surface profile could alter the applied grip force. On the other hand, with the presence of vibration, one study found that a vibrating surface was perceived to be rougher than a static surface although both surfaces had the same smoothness (Hollins et al., 2001). This could expound the effect of vibration on perceived surface smoothness or roughness.

In this study, constant vibration and grip force was pre-imposed, hence the difference between smooth and patterned surface profile could have elicited the effects on finger sensitivity. Unlike the smooth surface, the patterned surface might have caused the vibration to propagate on a deeper layer of the skin due to the rounded spikes that were prodded on the fingers. The effect of surface profile was apparent on elliptic-shaped handles because of the evenly distributed forces on the distal and proximal phalanges when grasping elliptic handles (Rossi et al., 2014). In addition, the ring and small fingers were affected because the forearm was pronated and this placed constant pressure on the hypothenar eminence, which affected the ulnar nerve (Dy & Mackinnon, 2016). Moreover, since the elbow was bent, the ulnar nerve was constantly stretched (Gelberman et al., 1998; James et al., 2011).

Perceived discomfort on the fingers and hand

Constant exposure to discomfort can lead to musculoskeletal disorders and can result to productivity loss. In this study, perceived discomfort on the fingers and hand were significantly higher on patterned surface than smooth surface specifically on circular and elliptic-shaped handles. This might be due to the rounded spikes on the patterned profile, which was prodded on the palmar skin while gripping the handle and possibly caused the vibration to intensify. Furthermore, even with the same grip exertion as the smooth-surfaced handles, the rounded spikes penetrated on the deeper skin layer of the palm and fingers and caused a more profound contact stress. Such patterned surface with wider grooves and directed contact force (perpendicular to the palm) were associated with higher perceived discomfort (Bobjer et al., 1993).

Grip comfort perception

In product development and design, comfort had a wide variety of definitions. Some common descriptions included sense of harmony between humans and their environment (Slater, 1985), experience of convenience after using the product (Vink et al., 2005), and the feeling of being physically free from pain (Dumur et al., 2004). In this study, grip comfort perception was described as the ability to consistently grip the handle, free from pain, considering some pre-imposed external stressors like constant vibration, moderate grip force, and awkward arm posture. It was found that surface profile influenced grip comfort perception, in which smooth surface had higher comfort ratings than patterned surface in all handle shapes. The reason for this might be similar to the perceived fingers and hand discomfort, wherein the rounded spikes on patterned surface penetrated deeply on the palm causing the vibration to propagate on a deeper skin layer.

5.4.4 Implications of implementing various handle shapes and surface profiles during exposure to vibration, sustained moderate grip force, and awkward arm posture

The use of handle grips posed lesser harmful effects than not using any, mainly because it provided additional layer of protection from the vibration source. With regards to shape, circular handles exhibited the least HTV because it generated the least total finger force, as discovered by previous studies. Meanwhile, elliptic-shaped handles exhibited higher HTV because of the homogenous finger force distribution during grasping, which also implied a higher palm and handle contact area. This also led to higher grip strength reduction as compared to other handle shapes. Finally, patterned surface elicited more negative effects than smooth surface profile on various handle shapes. Specifically, E_P had lower ring and small finger sensitivity, E_P and C_P had higher perceived discomfort on the fingers and hand, and E_P, C_P, and D_P had lower grip comfort rating than their smooth-surfaced counterpart. Essentially, handle shape seemed to influence vibration transmissibility and force exertion while surface profile affected comfort and sensation.

With the significant findings in this study, it can be said that elliptic-shaped handles, especially with patterned surface profile, could instigate more harm to the hand area during constant handle vibration, moderate grip exertion, and poor forearm posture. On the other hand, circular-shaped handles posed lesser harmful effects specifically on HTV and double-frustum handles on grip strength reduction.

5.4.5 Limitations of the study

This study only focused on the effects of various handle shapes, surface profiles, and solid layer in a laboratory set-up with some pre-imposed external stressors like HAV, constant grip force, and awkward arm posture on some physiological responses and hand functions. Meanwhile, other important aspects like effects on handle operability or sturdiness of the handle grip, which are also key factors when proposing a new design, were not considered.

5.5 Conclusion

With constant handle vibration, moderate grip exertion, and unnatural forearm posture, HTV was lower on circular-shaped handles, grip strength reduction was highest on elliptic-shaped handles, ring and small finger sensitivity were lower on patterned-surfaced than smooth-surfaced elliptic handles, perceived discomfort on the fingers and hand were higher on patterned-surfaced than smooth-surfaced elliptic and circular handles, and grip comfort perception was lower on patterned-surfaced handles that their smooth-surfaced counterpart. In conclusion, circular and double-frustum instigated less transmissibility and strength reduction than elliptic handles, while surface profile was a significant consideration for elliptic handles because the distinction can affect finger sensation, perceived discomfort on the fingers and hand, and grip comfort perception.

Chapter 6. General Discussion and Conclusion

6.1 Summary

The development of mechanized equipment improved work productivity and efficiency but highly exposed the workers to occupational vibration. In the Philippines, agricultural machineries have been mechanized to speed-up the farming process. However, previous research discovered that the vibration transmitted to the hand-arm system of hand tractor operators exceeds the allowable safety value (Layaoen et al., 2015; Revilla et al., 2015). Prolonged exposure to such level of vibration, as well as poor hand-arm postures and forceful movements, can cause serious and permanent illnesses to the hands and arms generally known as HAVS. Thus, it is important to detect the symptoms of HAVS at the early stages of exposure before it can affect fundamental hand functions such as strength, dexterous movement, and sensitivity. Majority of previous related research focused on replicating the influence of one-handle powered tool (Egan et al., 1996; Forouharmajd et al., 2017; Malchaire et al., 1998; Thonnard et al., 1997; Widia & Dawal, 2011; Xu et al., 2017). Meanwhile, this dissertation simulated a dual-handle or hand-guided powered machinery that is also a common source of HAV. The primary difference between the two types of equipment is the required grip force and arm posture during operation. In turn, this can affect the magnitude of transmitted vibration and its effects on the hands and arms. Moreover, design parameters can also vary. The main objective of this dissertation is to provide new and holistic insights about the immediate physiological effects of short-term exposure to constant handle vibration, sustained grip force levels, and various forearm postures on the hand-arm system and how various handle shapes and surface profiles can influence the effects.

Chapter 2 was a preliminary study on the effects of short-term handle vibration. This chapter compared two conditions: no vibration (NV) and with vibration (V) task wherein both employed unmonitored and self-imposed grip force and neutral forearm posture during exposure. In such condition, some symptoms of musculoskeletal disorder were observed, specifically on the onset of forearm muscle fatigue during maximum grip strength test and manifestation of shoulder discomfort.

Chapter 3 further explored the exclusive effects of handle vibration by comparing NV and V conditions wherein both instigated pre-imposed grip force and forearm posture. Essentially, sustained moderate grip force and neutral forearm posture were required and monitored while holding the handlebar for 5 min. This chapter demonstrated the exclusive effects of handle vibration during short-term exposure, which emphasized that the onset of HAVS symptoms, specifically the neurological and musculoskeletal components, are evident even during the early stages of exposure of healthy individuals. The recognizable symptoms, such as loss of finger sensation and manifestation of upper limb discomfort, can be easily assessed using non-invasive tests. Thus, implementation of temporary preventive measures can be done immediately.

Chapter 4 dwelled deeper on the effects of various hand-arm biomechanics during short-term handle vibration, in which the combinations of two grip force levels and two forearm postures, when using dual-handle equipment, were examined. The second study discovered the importance of forearm posture, particularly during forceful movements, when handling hand-guided powered equipment. The major findings can be a basis for manufacturers of such machineries to avoid making handlebars that demand the users to operate in pronated forearm, essentially if the tasks involved sustained hard grip or forceful movement. Instead, a handlebar requiring a neutral forearm would be a better option between the two handlebar designs. On the other hand, both handlebar structures are recommended when the tasks only require mild gripping.

Chapter 5 aimed to reduce the harmful effects of handle vibration, sustained grip force, and poor forearm posture through exploring the influence of various handle shapes and surface profiles on the hand and arm physiology. The third study showed the significance of implementing a handle grip and the influence of various handle shapes and surface profiles, specifically during moderate grip exertion and pronated forearm posture. A regular-sized circular handle grip can minimize the amount of vibration transmitted to the hand area and it can lower the discomfort perceived by the hand-arm system, as compared to not using any handle grip. Furthermore, an elliptic-shaped handle posed more harmful effects like higher hand vibration transmissibility than circular handle and higher grip strength reduction than double-frustum handle. The distinctions between smooth and patterned surface profiles were also apparent on elliptic handles, wherein patterned surface caused more negative effects on the hands and arms. Thus, a smooth-surfaced circular handle is suggested for minimal transmissibility while a smooth-surfaced double-frustum handle is proposed for consistent grip and an elliptic-shaped handle is not recommended.

6.2 Implications

The general findings can be summarized and classified into four key points, namely the effects of HAV, grip force level, forearm posture, and handle grip design.

6.2.1 Effects of handle vibration

The effects of short-term HAV are the primary focus of this dissertation. It was found that a 5-min exposure can cause higher discomfort to the hand, temporary loss of finger sensitivity, and reduced ability to grip consistently, even during moderate exertion. These findings are largely associated with the amount of vibration transmitted to the upper limb. In general, vibration frequency characteristics can affect how vibration propagates along the upper extremity (Aatola, 1989; Pyykko et al., 1976; Reynolds & Angevine, 1977). In this dissertation, the vibration source has a nominal frequency of 60 Hz, which implies that peak amplitudes can be observed in multiples of this frequency, specifically within three major bands: (1) 58~63, (2) 117~124, and (3) 177~182 Hz. Along these frequency bands, majority of the vibration is absorbed by the hand and forearm while very minimal is transmitted to the upper arm. Since the hand area absorbs majority of the vibration before it is transmitted to the upper limb, the fingers and hand had higher perceived discomfort as observed in Chapters 3, 4, and 5. Consequently, this can affect the ability to grip consistently. In addition, the amount of vibration that propagates on the soft tissues of the palm can result to tactile impairment, which is evident on temporary loss of finger sensitivity found in Chapters 3 and 5. Similarly, this can affect dexterous hand movement such as the ability to grip strongly or consistently. In summary, short-term exposure to HAV can stimulate the onset of peripheral neuropathy such as temporary loss of finger sensitivity and can instigate distal arm discomfort that can lead to upper limb musculoskeletal disorders, specifically if exposure duration is not regulated. In turn, these neurological and musculoskeletal symptoms can result to grip impairment.

6.2.2 Effects of grip force level

This dissertation also demonstrated the impacts of different grip exertions classified as mild, moderate, and hard, which are approximately 10%, 30%, and 50% of the maximum grip strength. Mild and hard grip forces were investigated in Chapter 4, while moderate grip force was explored in Chapters 3 and 5. The effects of various grip force levels are evident on forearm muscle activities, distal and proximal arm discomfort, and grip strength reduction. Among the three levels, sustained mild grip during short-term vibration exposure did not stimulate any recognizable symptoms of HAVS. In this force exertion, forearm muscles activated below 15% MVC and caused mild to moderate distal arm discomfort. Moreover, only mild discomfort was perceived along the proximal arm, which indicates that the impacts are mainly concentrated on the fingers, hand, and forearm. However, these impacts are minimal and did not indicate any clear signs of neurological or musculoskeletal disorders. Meanwhile, the onset of musculoskeletal components of HAVS is apparent after sustained moderate grip. This level instigated higher forearm muscle activities than mild grip and caused moderate to severe distal arm discomfort. Although, similarly, the perceived discomfort along the proximal arm was mild, which also implies that in this force exertion, most of the impacts are focused on the fingers, hand, and forearm. Lastly, sustained hard grip led to clear manifestations of HAVS that is not only evident on higher forearm muscle activities and moderate to severe distal arm discomfort but is also noticeable on significantly higher grip strength reduction and moderate to severe proximal arm discomfort. Essentially, this force exertion caused intense physical stress along the entire upper limb that further led to reduced hand strength. In summary, the progression of HAVS symptoms, specifically the musculoskeletal aspects, are directly influenced by grip force levels. Mild to moderate grip exertion can affect the fingers, hand, and forearm while sustained hard grip can reduce hand strength and can stress the whole upper extremity.

6.2.3 Effects of forearm posture

The effects of forearm posture were clear on hard grip and indistinctive on mild grip, as discovered in Chapter 4. Hard grip on pronated forearm, can intensify the effects of short-term handle vibration through lower FF activation as a function of exposure time and higher proximal arm discomfort, as compared to hard grip on neutral forearm posture. The relationship between grip ability and forearm posture can explain the difference in FF contraction and upper arm discomfort. Previous research indicate that pronated forearm yields lower grip strength than neutral or supinated forearm (Fan et al., 2019; Mogk & Keir, 2003; Murugan et al., 2013; Richards et al., 1996) because of the unnatural position of the FF and other related muscles on pronated posture (Brand & Hollister, 1993). During forearm pronation, the FF wraps around the radius (Brand & Hollister, 1993; Richards et al., 1996); hence it could not contract optimally resulting to lower activation. In addition, the upper arm muscles are involved when changing forearm postures (Güleçyüz et al., 2017; Naito et al., 1995), specifically an electromyographic study showed a clear contraction gain on the brachialis and brachioradialis activities during slow supination to pronation movement (Naito, et al., 1994). This explains why the proximal arm had higher perceived discomfort on pronated than neutral posture since it is more engaged during pronation. In summary, the effects of poor forearm posture on the development of musculoskeletal aspects of HAVS are emphasized when combined with forceful movement.

6.2.4 Effects of handle grip design

Given the cumulative effects of handle vibration, forceful movement, and awkward posture when using hand-guided powered equipment, some proposed handle grip designs, which aimed to limit the development of HAVS, were investigated in Chapter 5. It was found that implementing a regular-sized circular handle provided additional layer of protection to the hand from the vibrating handle, which led to lower vibration transmissibility. Consequently, this resulted to lower hand-arm discomfort and higher grip comfort. In addition, it was discovered that handle shape influences vibration transmissibility and force exertion while surface profile affects sensation and comfort. Handle shape affects finger force distribution and finger joint postures since the hand and handle contact area also varies with handle contour (shown in Figure 6.1), which can modify finger coordination. The unevenness of finger coordination can impact contact stiffness and grip stability, henceforth affects HTV. Previous research found that circular and double-frustum handles generate the least total finger force (Kong et al., 2008). This can suggest why, in Chapter 4, vibration transmissibility on circular handle was lower compared to other handle shapes. Similarly, the degree of hand and handle contact area can be associated with grip strength reduction. Specifically, on elliptic handle where the contact area is greater than the other two handle shapes (shown in Figure 6.1 (c)), the reduction on grip strength was significantly higher. This implies that when a larger palm area is under contact stress, it allows vibration to propagate on a bigger area as well. During such contact stress, soft tissues of the palm are compressed between the metacarpal and the vibrating handle. This can result to temporary loss of sensation, which is essential to dexterous hand functions such as gripping (Zatsiorsky & Latash, 2004), thereby reducing grip ability. In summary, a handle shape that causes too much contact stress can provide more harmful effects, particularly on the development of upper limb musculoskeletal illnesses.

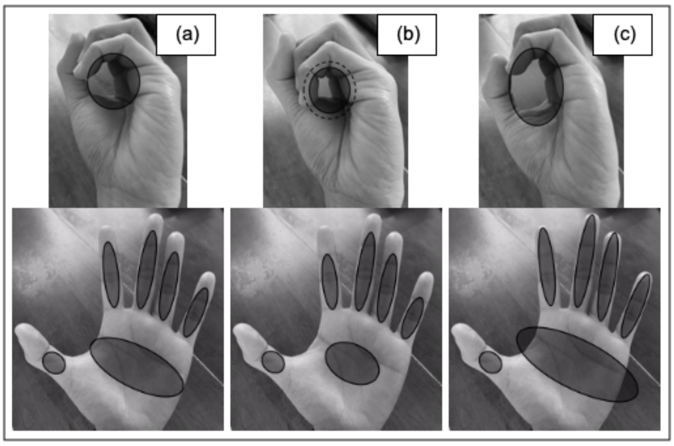

Figure 6.1. Illustration of the hand and handle contact area on: (a) circular, (b) double-frustum, and (c) elliptic-shaped handles.

Meanwhile, the main effects of handle surface profile were evident on elliptic handle and not on other handle shapes. The ring and small finger sensitivity were lower on patterned surface than smooth surface. Surface profile provides frictional condition, which gives stability and steadiness to the level of grip exertion (Cadoret & Smith, 1996; Flanagan & Wing, 1995; Johansson & Westling, 1984). The rounded spikes on patterned surface that are prodded on the fingers due to contact stress may have caused the vibration to propagate on a deeper layer of the palm. Moreover, since the contact forces on the distal and proximal phalanges are evenly distributed when grasping elliptic handles (shown in Figure 6.1 (c)), a larger palm area was propagated by vibration. This explains how sensitivity was affected on patterned surface. The effect was specific on the ring and small fingers because the forearm was pronated during the task and this placed constant pressure on the hypothenar eminence, which affected the ulnar nerve (Dy & Mackinnon, 2016). Similarly, the more profound contact stress brought by the rounded spikes on patterned surface influenced higher fingers and hand discomfort and lower grip comfort. In summary, the effects of surface profile are intensified by the hand and handle contact area, which also depends on the handle shape. Its influence is apparent on the neurological aspect of HAVS such as loss of finger sensitivity and musculoskeletal symptoms like fingers and hand discomfort.

6.2.5 Summary of findings

Figure 6.2 summarizes the effects of handle vibration, grip force level, and forearm posture on the hand-arm system. Each quadrant represents major findings on every grip force level and forearm posture combination investigated in Chapters 3, 4, and 5. For instance, Quadrant III briefly demonstrates the results found in Chapter 3. Quadrants I, II, V, and VI are the findings on Chapter 4. Finally, Quadrant IV is the condition used for Chapter 5, where various handle shapes and surface profiles were examined. Meanwhile, the results in Chapter 2 were not indicated in Figure 6.2 since the grip force level and forearm posture in this preliminary study were self-imposed and not explicitly monitored during the exposure duration.

	Mild grip force	Moderate grip force	Hard grip force
Pronated forearm (unnatural posture)	**Q II** Chapter 4 1. WTV = 14% 2. GS reduction = 14% 3. DA discomfort = mild to moderate 4. PA discomfort = mild 5. % MVC of forearm muscles = 5-14%	**Q IV** Chapter 5 1. WTV = 17% 2. HTV = 70% 3. GS reduction = 23% 4. DA discomfort = moderate 5. PA discomfort = mild 6. % MVC of forearm muscles = 12-30%	**Q VI** Chapter 4 1. WTV = 22% 2. GS reduction = 34% 3. DA discomfort = severe 4. PA discomfort = moderate to severe 5. % MVC of forearm muscles = 13-33%
Neutral forearm (natural posture)	**Q I** Chapter 4 1. WTV = 17% 2. GS reduction = 12% 3. DA discomfort = mild to moderate 4. PA discomfort = mild 5. % MVC of forearm muscles = 4-15%	**Q III** Chapter 3 1. WTV = no data 2. HTV = no data 3. GS reduction = 15% 4. Middle finger sensitivity = decreased 5. DA discomfort = moderate to severe 6. PA discomfort = mild 7. % MVC of forearm muscles = 7-25%	**Q V** Chapter 4 1. WTV = 17% 2. GS reduction = 27% 3. DA discomfort = moderate to severe 4. PA discomfort = mild to moderate 5. % MVC of forearm muscles = 13-39%

Figure 6.2. Relevant findings contributing to the progression of HAVS, based on grip force level and forearm posture, from least (Q I and II) to most impactful (Q VI).
Note: DA = distal arm; GS = grip strength; PA = proximal arm; WTV = wrist transmitted vibration.

In every quadrant, some of the common indicators considered in each study such as transmitted vibration, grip strength reduction, upper limb discomfort, and forearm muscle activities are listed. Notably, the magnitude of these parameters progresses with grip force level (mild grip to hard grip) while the influence of forearm posture is particularly distinctive on hard grip.

In summary, the development of HAVS symptoms increases with grip force exertion, even during short-term handle vibration exposure (shown in Figure 6.3). Mild grip does not stimulate any recognizable symptoms while hard grip (Quadrant VII) instigates clear signs of musculoskeletal disorders. Temporary loss of finger sensitivity and development of moderate upper limb discomfort start to manifest during moderate grip on both forearm postures, while higher grip strength reduction, severe upper limb discomfort, and higher forearm muscle activities occur during hard grip exertion. Generally, mild grip on neutral forearm (Q I) or pronated forearm (Q II) pose the least manifestation of HAVS symptoms while hard grip on pronated forearm (Q VI) stimulates the most apparent indication of HAVS.

	Mild grip force	Moderate grip force	Hard grip force	
Pronated forearm (unnatural posture)	**Q II** Did not stimulate any recognizable symptoms of HAVS	**Q IV** Basis for recommending various handle shapes and surface profiles The implications are elaborated in Section 6.2.4	**Q VI** Higher wrist vibration transmissibility Stimulated musculoskeletal symptoms of HAVS such as: (1) increased proximal arm discomfort (2) lower FF activity through time	**Q VII** Higher wrist and elbow vibration transmissibility Stimulated musculoskeletal symptoms of HAVS such as: (1) higher grip strength reduction (2) higher distal arm discomfort (3) higher forearm muscle activities
Neutral forearm (natural posture)	**Q I** Did not stimulate any recognizable symptoms of HAVS	**Q III** Stimulated neurological and musculoskeletal symptoms of HAVS such as: (1) temporary loss of finger sensitivity (2) increased distal arm discomfort (3) reduced ability to sustain a grip	**Q V**	

Figure 6.3. Major implications of the relevant findings on the development of HAVS.

6.3 General recommendation

The cumulative effects of handle vibration, forceful movement, and poor posture during short exposure duration are presented in this dissertation. It is proposed that when designing any work condition involving HAV, the primary consideration is force exertion. The application of sustained and intense grip force should be avoided, even for short-term exposure, because it is directly associated with the early development of upper limb musculoskeletal disorders. Instead, moderate force exertion can be imposed for brief tasks that is less than 5 min while the application of mild force is highly suggested for activities with longer duration. Secondly, it is recommended that forearm posture be considered when the tasks involved forceful movements. Essentially, imposing neutral forearm is suggested and pronated forearm should be avoided, since this condition stimulates the most apparent manifestation of HAVS symptoms. Finally, implementing a smooth-textured handle grip having a shape that reduces the hand and handle contact stress without compromising operability and maneuverability is proposed. From this dissertation, a circular or double-frustum-shaped handle with an outer diameter of approximately 33 mm is preferred than elliptic-shaped handle. This can limit HTV and regulate the development of neurological and musculoskeletal components of HAVS.

6.4 Limitations and future studies

This dissertation was able to establish baseline analyses on the effects of handle vibration, various grip force levels, and two common forearm postures on the hands and arms. However, there are some limitations and factors that were not considered. Primarily, the required grip exertions during task performance were monitored using the activity of ECR. Although previous research support that ECR activity is closely similar to the actual grip force (Mogk & Keir, 2003; Norris, 2011), some discrepancies are observed and may be avoided if force sensors are used. Hence, the use of such sensors is suggested for future studies to easily monitor the actual grip exertion. Secondly, this dissertation focused on static grip force and forearm posture and did not consider various dynamic movements such as pushing, pulling, lifting, or maneuvering the handle, which are common motions when operating in actual work conditions. These movements can also influence the effects of handle vibration and operability of the handle structure; hence these would be a substantial consideration for future studies. Lastly, majority of the measurement and tests were performed on one hand or arm, either the dominant or non-dominant side. It would be interesting to compare the effects between both hand sides since force exertion and posture of both hands and arms may not be the same at all times.

6.5 Conclusion

The effects and implications of short-term HAV, grip force levels, and forearm postures on the hand-arm functionality and physiology, specifically on the development of HAVS symptoms, were demonstrated in this dissertation. In addition, Chapter 5 showed the importance of implementing a handle grip and suggested how various shapes and surface profiles can minimize or aggravate the effects of work conditions involving handle vibration. In conclusion, the effects of short-term HAV on the neurological and musculoskeletal aspects of HAVS are apparent on the temporary loss of finger sensitivity and increased distal arm discomfort that lead to grip impairment. Furthermore, the application of hard grip force and poor forearm posture aggravates the effects of handle vibration, which leads to higher wrist vibration transmissibility, higher grip strength reduction, higher forearm muscle exertion, and higher proximal arm discomfort. Finally, implementing a handle grip lowers hand and wrist vibration transmissibility resulting to lower hand-arm discomfort, while varying the handle shape influences transmitted vibration and force exertion and changing the surface profile affects sensation and comfort.

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