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COMBINED EFFECTS OF FORCE AND VIBRATION ON THE HUMAN HAND

by

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Abstract

The combined effect of force and hand-arm vibration (HAV) exposure on human hand is considered to be highly influential, yet it remains an understudied area of research. This study aimed to investigate the acute effect of hand force during vibration exposure on human physiological responses, particularly focusing on the neural and vascular systems. It was an experiment-based study that examined the acute effects on healthy subjects by exposing them to various combinations of force loadings and vibrations.

The first study focused on the vibration-induced vascular effects, specifically the weakening of peripheral blood circulation. Participants experienced different force levels and moderate vibrations. Measurements of finger blood flow and finger skin temperature were conducted during and after the exposure to force and vibration. The results revealed that hand force had a stronger influence on circulation than vibration. Clear reductions in finger blood flow and finger skin temperature were observed with hand force, while the additional impact of vibration was not significant. Moreover, a higher grip force exerted a greater influence on circulation compared to a push force.

The second study focused on the vibration-induced neurological effects, particularly temporary shifts in vibration and thermal perception thresholds. Participants were exposed to different conditions with two levels of vibration and moderate force levels. Measurements on thresholds were tested following vibration and force exposure. The results showed vibration levels significantly influenced neurological responses. Hand force had a notable effect on small vibration magnitudes but diminished for larger vibrations.

In the third study, the acute vascular response to short-term HAV was further investigated. Participants underwent a similar experimental procedure with the same combinations of force loadings and vibrations as in the second study, but with a slightly different posture. Combining the results of the second and third studies, it was observed that both the nervous and circulatory systems were sensitive to force and vibration. Responses decreased as vibration and force intensity increased, with the nervous system showing higher sensitivity to vibration.

The final study aimed to refine the exposure conditions to quantify the cause-effect relationship between force, vibration stimuli and the physiological response. Both factors were expanded on a larger scale to assess their relative significance. Temporary shifts in vibration perception thresholds were used for analysis. A fitting of the response results was provided, demonstrating that human responses were influenced by both force and vibration levels, highlighting their interdependent relationship.

Keywords: hand-arm vibration, force exertion, vascular and neural responses

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Definitions and Abbreviations

BMI..... Body Mass Index

CPT..... Current perception threshold

CST..... Cold-stress tests

CTS..... Carpal tunnel syndrome

ERGO..... Ethics and Research Governance Online

FE..... Finite element

FEPS..... Faculty of Engineering & Physical Sciences

FST..... Finger skin temperature

FBF..... Finger blood flow

FSBP..... Finger systolic blood pressure

GAT..... Grip ability test

HAV..... Hand arm vibration

HAVS..... Hand-arm vibration syndrome

HH..... Hypothenar hammer

HSE..... Health and Safety Executive

IQR..... Inter-Quartile Range

ISO..... International Organization for Standardization

ISVR..... Institute of Sound and Vibration Research

m. ..... Muscle

MCP..... Metacarpophalangeal

NCS..... Nerve conduction studies

NP..... Non-Pacinian

P ..... Pacinian

PC..... Pacinian corpuscle

PPE..... Personal protective equipment

QST..... Quantitative sensory testing

RP..... Raynaud's phenomenon

SD..... Standard deviation

SSN..... Stockholm Sensorineural

SWS..... Stockholm Workshop scale

TA..... Thermal Aesthesiometer

TNZ..... Thermal neutral zone

TOS..... Thoracic outlet syndrome

TP ..... Taylor Pelmear

TPT ..... Thermotactile perception threshold

TPTc ..... Thermotactile perception threshold for cold

TPTw ..... Thermotactile perception threshold for warmth

TTS ..... Temporary threshold shift

TVR..... Tonic vibration reflex

VPM ..... Vibrotactile Perception Meter

VPT..... Vibrotactile perception threshold

VR..... Virtual reality

VWF ..... Vibration-induced white finger

Chapter 1 General introduction

1.1 Hand-arm vibration

Hand-transmitted vibration, also referred to as hand-arm vibration (HAV), commonly occurs to an individual when holding a vibrating machine (Griffin and Erdreich 1991). Potential sources cover a wide range of industrial tools and machinery, including powered surgical instruments, demolition picks, riveting guns, in addition to some non-occupational exposure objects like motorcycle handlebars, hair clippers, etc. The hand-arm system has a complex dynamic response to the vibration source which in the long run is associated with various disorders, by tradition collectively referred to as hand-arm vibration syndrome (HAVS), in the vascular, sensorineural and musculoskeletal aspects (Bovenzi et al. 1999, Ye and Griffin 2018, Hagberg 2002). Recent research also discusses the risk of Carpal Tunnel Syndrome (CTS) and Dupuytren's contracture in relation to vibration exposure (Cooke and Lawson 2022, Vihlborg et al. 2022, Mathieu et al. 2020, Nilsson et al. 2023). Therefore, engaging in occupations that require prolonged exposure to HAV can lead to not only disabling pain in the hands of the workers but also permanent damage in their blood vessels, nerves, muscles, and joints, which is bound to cause a loss of strength and feeling in the hands and affect the ability to carry out fine work.

The most representative and common syndrome is vascular disorder, which is known as the vibration-induced white finger (VWF) because of the cessation of blood supply and a resultant loss of colour in the fingers provoked by exposure to cold or stress (Griffin and Bovenzi 2002). The initial manifestation of the symptom is the witness of white in the fingertips. With the ongoing vibration exposure, conditions can be exacerbated as the digit vasoconstriction becomes more severe and the area affected by blanching will gradually expand proximally to the palm. It remains unclear how to link vibration with the prevalence of VWF, but an accepted explanation for the syndrome is impaired neurosensory function or flow occlusion caused by damaged capillaries (Pelmear and Wasserman 1998).

1.2 Status quo of HAV related issues

With manufacturing still playing an important role in the industry, populations affected by HAV become apparent especially under the impetus of globalization. In China, for instance, about 2 million people are at risk of suffering from occupational health problems induced by HAV (Xing et al. 2011, Xiao et al. 2019). For some specific types of work, the proportion of workers with HAVS can achieve 80% (Wasserman 1982). At the same time, the health issue has an impact on the economy and society. According to epidemiological statistics, the average age of workers diagnosed

to have VWF is 33.8 years old, while the average year of service is only 9.2 years (Xing et al. 2011). Once the VWF occurs, it is lack of treatment, and the workers have to stop working to avoid a worse situation. That means most workers in some particular area can only work no more than 10 years. It is a tragedy especially for those skilful workers who did a lot of training. After stopping work, they have to change job or to live on a subsidy either from the enterprise or from the government. As a result, the state loses a large number of young labours and the government has to provide them with economic guarantees to cover their future living expense.

In recent years, more details are given in International and European Standards on diagnostic criteria of occupational HAV disease. Attention has been paid towards health prevention by exposure reduction, health surveillance and treatment of occupational diseases, but the progress of related programs suffers from many limitations. On the one hand, the underlying mechanisms responsible for disorders arising from exposures to HAV are not fully clear. Without a deeper understanding of intrinsic pathophysiology, people cannot assure the accuracy and specificity of the assessment for HAV syndrome or the risk of developing a more serious syndrome. On the other hand, for the affected workers, problems eager to be solved involve the lack of exclusive diagnosis as well as prevention measures such as hand gloves that cannot meet the requirement in achieving good performance of the operation (Rezali et al. 2014). In the meantime, the current measurement standards (ISO 13091-1: 2001) and (ISO 5349-1:2001) for general considerations of quantities and measuring equipment are still not useful due to a lack of risk assessment models. As a result, issues mentioned above like pathogenic mechanisms, risk factors and prevention can all lead to overdue actions to prevent the disease and shorten the career life of the workers.

1.3 Possible applications

Research on human factors engineering focuses on the human response to the HAV, helping in the address of the health issue. Firstly, seeking the HAV effects in various indicators of affected tissues supports the accurate identification and staging of HAVS. Secondly, with the awareness of influential factors and underlying mechanisms, applying prevention techniques to related products and priming reasonable “rest” models makes it possible to stop people from developing HAVS and makes sense for symptom relief for sufferers. If efforts can be devoted to projects on the HAV with a range of actions implemented in parallel so as to predict and even prevent the occurrence of HAVS in the early stage, it will definitely improve the work safety and efficiency of the labour force and reduce considerable financial expenditure.

1.4 Research objectives

The intention of the entire study is, in a word, to help identify the mechanisms responsible for the HAV-induced effects, especially the contribution of the risk factors involved.

Upon reviewing the existing work, as shown in Chapter 2 Literature Review, certain limitations in terms of short-term effect of HAV have come to the fore. The role of the level and manner of hand force exertion during the use of vibration tools is not well documented, and its physiological effects in the standard for assessing the vibration exposure amount is absent. Such factors likely to influence the effects of human exposure to HAV are only commented on in Annex D of the ISO 5349-1 standard (ISO 2001a). As a result, this research delves into the realm of HAV, exploring its pathological effects combined with different influencing factors, especially hand forces, on individuals.

To propel this quest for knowledge forward, the first step is to explore how the response to vibration changes as a function of hand force. This exploration will not only identify the ability to detect the response of the hand-arm system, but also determine the importance and interplay of the two influencing factors (force and vibration).

The aim is then to figure out a cause-effect relationship by fitting an empirical model that rules out the effect of inter-individual varieties but takes the vibration and forces into account. Experiments will be carried out to collect laboratory data to derive the formula and propose the model.

1.5 Thesis outline

Being an experiment-based study, the thesis outline is as follows:

Chapter 1 introduces the domain of research addressed in this thesis.

Chapter 2 presents a review of the literature pertaining to the anatomical structure, as well as the human physiological responses to the hand-arm vibration, while also exploring the interaction and modification of factors.

Chapter 3 provides an introduction of the instruments and methodologies employed in the experiments.

Chapter 4 to 7 encompass a detailed account of the experiments conducted in this research, encompassing their processes and outcomes. These experiments were designed to address specific research questions, which are:

Q I. To what extent does the application of hand force during exposure to vibration influence the regulation of the circulatory response? Furthermore, which types of hand force have the most significant effect?

Q II. In terms of sensitivity, is the response primarily influenced by force or vibration? Additionally, does this effect extend to the nervous system?

Q III. Are there any interconnections or inherent differences between the responses of the two systems, namely the vascular system and the nervous system? Does the posture adopted during exposure have any effect on these responses?

Q IV. Can the relationship between force-and-vibration exposure and the human response be quantified?

Chapter 8 provides a summary and in-depth discussion of the experimental results obtained throughout this thesis. It highlights the limitations encountered during the research process and suggests potential areas for future exploration and study.

Chapter 2 Literature review

2.1 Anatomy of the hand-arm system

The human hand is the part of the hand-arm system that is in direct contact with the vibration source. However, the functional impact of vibration-induced injury to the hand is often out of proportion with the extent of the injury itself. As a result, a solid understanding of the pathology requires a good grasp of the anatomy of the hand along with that of the upper limb. In this part, we will have a look at the related anatomical structures.

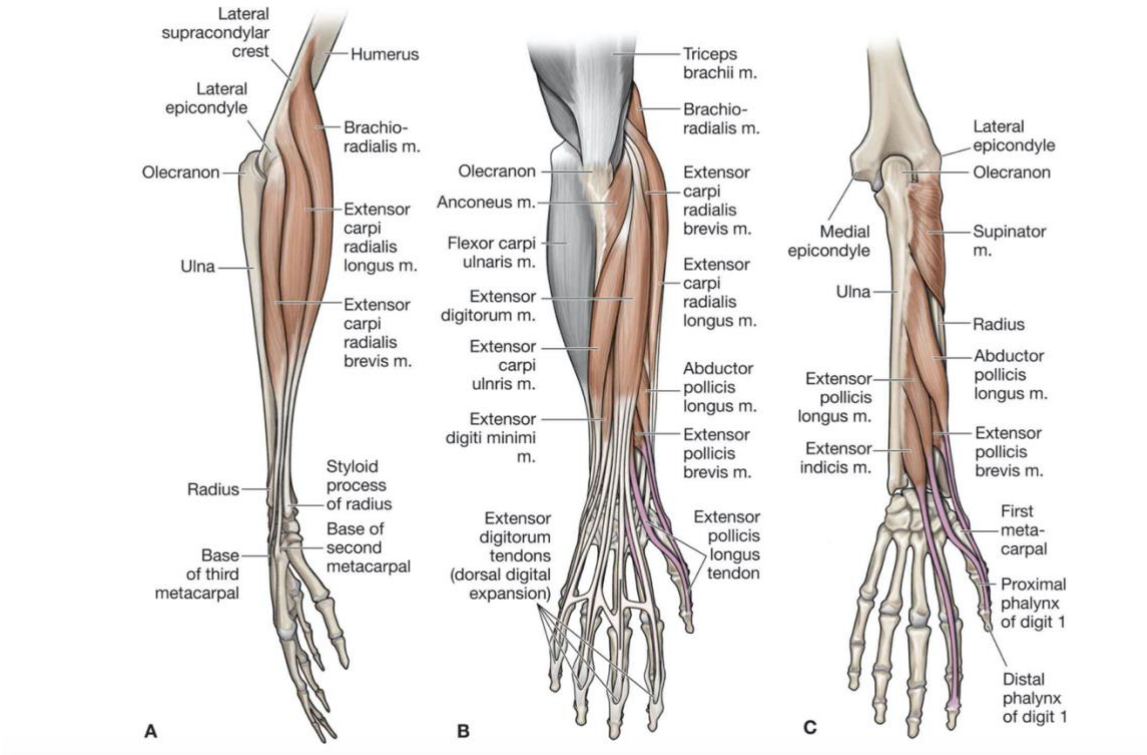


Figure 2-1 Musculoskeletal structure of upper extremity (Morton 2011).

The human upper extremity is made up of shoulder, axilla, upper arm, elbow, forearm, wrist, and hand (Palastanga et al. 2002). The different parts are independently mobile and equipped with adequate strength so as to move around the body or position specific parts of them controlled by the central nervous system. Figure **2-1** above shows the musculoskeletal anatomy of the hand, wrist, and forearm, which are the main areas affected by HAV.

In a sense, the upper limb is designed to contribute to the usefulness of hands (Sellers 2002): long bones and flexible joints provide a wide range of motion; muscles of the arm absorb energy elastically and run down the wrist and hand to keep them moving, stable, and well-aligned; the nervous system and vascular system are also in place to provide adequate supply to the hand. The

synchronization and interplay between these upper limb components during the activities of life ensures great dexterity and precision, as well as protecting the head and hand when the upper part of the body is in motion.

The human hand is an extraordinary triumph of natural engineering. It accounts for about 90% of upper extremity function (Capek et al. 2018), not only strong enough for a powerful grasping action, but also sufficiently precise to perform fine motor tasks. This extreme adjustability relies on the considerably complex design of the hand structure. The hand is made up of a delicate skeleton onto which various muscles are attached, playing a significant role in wrist and finger function (Maitland et al. 2005). Moreover, the hand entails a collection of vascular and neural structures. Such a complex neurovascular network is responsible for the drainage and innervation of the hand, which are specified with other anatomical structures in Table ***2-1***.

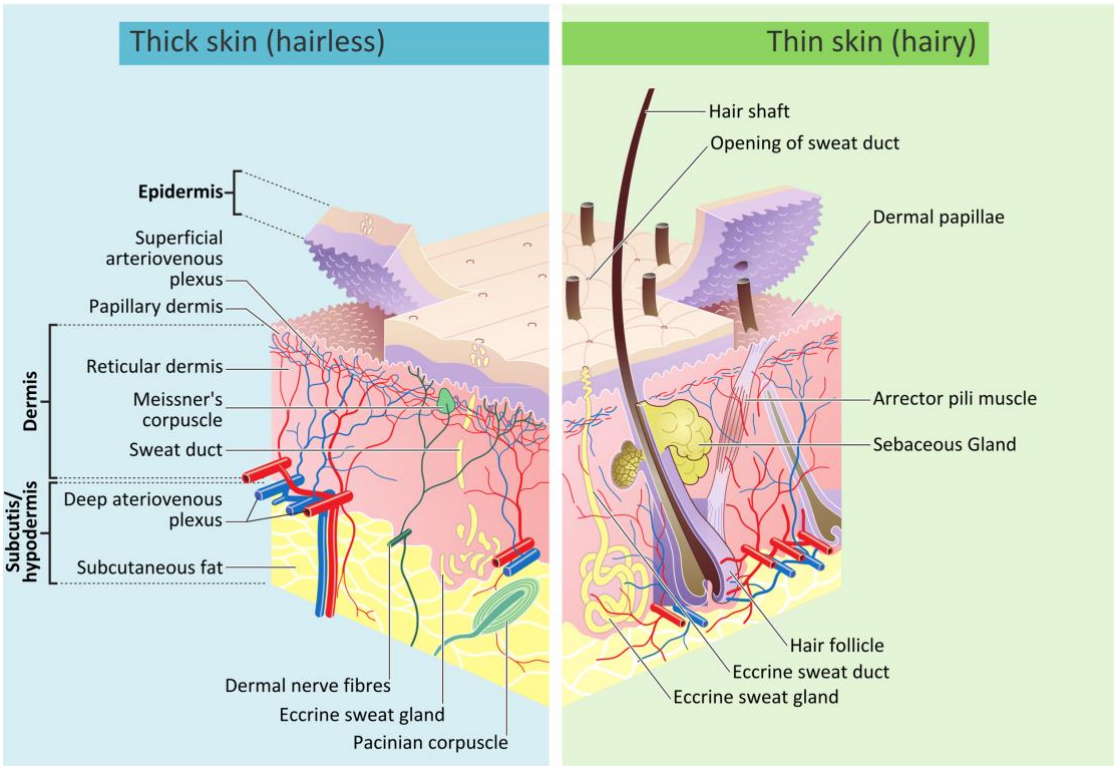


Figure 2-2 Anatomy of the integumentary system of the thick (hairless) skin and thin (hairy) skin. (Contributed by Wikimedia Commons, USGOV (Public Domain))

The other thing is the skin on the hands (and feet) feels different from that on most other areas of the body. That is because the skin on the palmar side of the hand is identified as 'thick skin' or 'glabrous skin' with unique patterns of ridges but no hairs (Fenner and Clark 2016). Thick (hairless) skin appears only in areas with plenty of abrasions such as fingertips, palms and soles of feet, while thin (hairy) skin covers the rest of the body (Lopez-Ojeda et al. 2019). As shown in Figure **2-2**, the hairless skin is characterised by a rich distribution of sensory end organs such as Pacinian corpuscles

(abundant in fingers) which are sensitive to gross pressure changes and hand-transmitted vibration (Biswas et al. 2014), and Meissner's corpuscles (distributed in palms) which are responsible for light tactile perception (Hoffmann et al. 2004).

It is the numerous structures that make up the hand and work together to give rise to so many hand functions. Table ***2-1*** describes the main contributors of those, detailing their respective composition, functions and possible damages.

Table 2-1 Key facts about the hand

bones	The hand is a complex system of many bones (Tubiana et al. 1998, Arias and Varacallo 2019): five elongated metacarpal bones located near the wrist that help form the palm; 14 phalanges that make up the fingers, each of which consisting of 3 phalanges, except for the thumb which consisting of 2. The bony configuration provides the hand with inherent stability. A joint is formed wherever two or more of these bones come together. In the hand, the metacarpophalangeal joint (MCP) (Drake et al. 2009) are responsible to join the fingers to the palm, and the interphalangeal (IP) joint links the fingers. All of these joints (knuckles) work like hinges, allowing the fingers and thumb to flex and stretch. The ends of the joint surfaces of joints are covered with articular cartilage (Bautista et al. 2016), with a white and slick look. Healthy cartilage is able to absorb shock and reduce friction when two bony surfaces glide against one another, but this material can be damaged by injury or repeated wear and tear.
ligaments	Ligaments are tough crisscross bands of fibrous tissue that connect bones and joints together (Ombregt 2013, Botte 2003). There are a great many ligaments derived from the hand and provide support to it, in which collateral ligaments are located laterally on each side of the digits and the volar plate connects the phalanges to the joints on the palm side. These ligaments are the primary stabilisers within the hand that help to keep all the bones in place and restrict the range of motion. There is another stabiliser denoted as joint capsule (Ralphs and Benjamin 1994), which is comprised of fibrous connective tissue that surrounds the articulating surfaces. The capsule is lined with an inner synovial membrane, also known as the synovium, which secretes a fluid to lubricate and nourish the joints. Joint capsules

tend to get stiffer with age and any excessive bending or laxity in a joint may damage ligaments and joint capsules.

muscles

Muscles acting on the hand are made up of two groups: the extrinsic and intrinsic muscle groups (Okwumabua et al. 2020, Raszewski and Varacallo 2018). The extrinsic group refers to the muscles that originate from the elbow or forearm and run down to cross the wrist and hand. Some of them serve to bend and straighten out the wrist. Others extend to the fingers and thumb to influence their performance, such as moving the thumb backwards, making grasping objects possible.

The intrinsic group are the smaller muscles situated in the wrist and hand. Thenar (thumb) muscles (Gupta and Michelsen-Jost 2012), hypothenar (pinkie) muscles (Pasquella and Levine 2012) and metacarpal muscles are the three major intrinsic muscles responsible for the fine movement of fingers. M. Palmaris brevis and m. adductor pollicis are also included in the group. They connect in ways that facilitate the extension, flexion, abduction, adduction and opposition of the phalanges. Each set of hand muscles has its own importance, working together to help get the wrist positioned and hold the hand steady during fingers gripping or performing fine motor actions.

Tendons in the hand are tough bands of connective tissue, located at the end of the muscles arising from the forearm and wrist, that attach the muscles to the bones of fingers and thumb. The tendons on the top of the hand that allow fingers to straighten are known as the extensors (Netter 2014). Those across the palm side of the hand that bend the finger joints are termed the flexor tendons (Allan 2005). These tendons are capable of withstanding the tension generated by muscular contraction to move the bones, and absorbing some of the impacts during hand activities. Damage to tendons is common to see in the hand, which can occur with a tear or a penetrating injury.

nerves

The hand is innervated by three major nerves that stem from the neck, come together at the shoulder and run the length of the entire arm: the radial nerve, the median nerve, and the ulnar nerve (Jones and Lederman 2006).

For one thing, the motor branches projecting onto the hand muscles come from the median and ulnar nerves. They carry signals from the brain, supply the muscles and make the hand move. The radial nerve, for another, only provides cutaneous

innervation when referring to the hand. Along with the other two nerves, it gives sensations about touch, pain and temperature back to the brain through sensory branches.

Nerves are fragile and easily subject to problems on the dominant hand. Cuts, pressure, constant bending and stretching, or crush injuries can result in pain and irritation on nerves and can cause a lack of sensation, movement, or both.

blood vessels

Travelling along with the nerves are two main large arteries: the radial and ulnar arteries (Husum and Palm 1978, Singh et al. 2017). They originate from the brachial artery at the elbow and run down the forelimb on the radial and ulnar sides respectively into the wrist, where they anastomose to form arterial arches: the superficial and the deep palmar arches. These arches further give off specific branches, all of which supply blood to the hand and fingers.

From the capillaries, blood passes back into venules, then into veins located near the arteries to return to the heart. The veins of the hand consist of the superficial and the deep palmar venous arches, dorsal hand venous network and palmar metacarpal digital veins, all of which drain into either the radial or ulnar veins (Drake et al. 2009). These veins are similar to arteries but thinner, more flexible and with lower pressure. Disorders in blood vessels are likely to occur among people working with vibrating tools, being in a cold environment, smoking and with diseases such as diabetes or kidney failure.

wrist

The wrist comprises multiple bones and joints (known as the carpal bones) that bridge the hand to the forearm (Baratz et al. 1999). In addition, there is also a network of soft tissues such as ligaments, tendons, nerves, and blood vessels, in and around the wrist. These soft tissues function together with the carpal bones to allow the movement of the wrist in different ways, and provide it with strength, stability and cushioning. In the meantime, sensation and nourishment from the forearm to the hand are also dependent on the passage of various neurovascular structures through the complex wrist structure. But excessive doing contact sports or using power tools can put individuals at higher risk of having a wrist problem such as Carpal tunnel syndrome (CTS) (Silverstein et al. 1987).

According to Paul W. Brand (1914–2003), “A hand is a very personal thing. It is the interface between the patient and his or her world. It is an emblem of strength, beauty, skill, sexuality, and sensibility. When it is damaged, it becomes a symbol of the vulnerability of the whole patient.” It's easy for people to take for granted the complexity of the hand-arm system when there is nothing wrong with it. However, changes in the way the hand structure works, and production activities at the expense of the overuse of hand-arm systems can greatly impact whether the hand develops abnormalities, say, HAVS. It is therefore important to have a basic understanding of the structures that control the use of hand-held tools in order for normal hand function to occur and maintain (Lundborg 2013).

2.2 Chronic effect: hand-arm vibration syndrome

As mentioned earlier, HAV is related to a wide range of chronic health effects and can even lead to the loss of functions and elicit symptoms. The symptoms of the affected systems include but are not limited to:

- Vascular system: bouts of the white finger (Raynaud's phenomenon)
- Nerve system: loss of sensory perception; digital tingling, and numbness
- Muscular system: muscle weakness; strength loss
- Skeletal system: minor trauma; aches and pains

Measures for testing the dysfunction in the hand-arm system to cold and vibration can assist in diagnosing and tracking the development of HAVS, in addition to existing symptoms and the fact of long work history.

2.2.1 Classification of HAVS vascular and neurosensory components staging (checklist methods)

2.2.1.1 The Stockholm Workshop scale on vascular injury

Checklist methods have been widely applied as a means of staging HAVS, in which the Stockholm Workshop scale (SWS) is the most common one for VWF (Gemne et al. 1987a). Based on the medical history and the photography of fingers appearing white, the stages progress from 1 to 5 for VWF cases from mild to very severe. Defining the grading system is made according to the collective experience of thousands of cases and their natural histories, but it should be appreciated that this method is not infallible given that VWF is a 'more or less' condition and patients might exaggerate the frequency of attacks or affected area for the expectation of compensation.

2.2.1.2 The Stockholm Workshop scale on neurosensory injury

Stockholm Sensorineural (SSN) scale is specifically aimed at the sensorineural stages of HAVS (Brammer et al. 1987). Occupational health practitioners are scored with a stage of OSN to 3SN that indicates the severity of sensory symptoms from no to the most severe. While for more complete criteria, consideration should also be given to monitoring where the sensory impairment occurs.

The extant classification methods also include Taylor Pelmear (TP) scale (Taylor 1974) which is able to simultaneously assess the reduction in vascular (VWF) and sensory function along with seasonal and disability aspects. New scales are being developed to better stage suspected cases of HAVS.

2.2.2 Diagnosis of HAVS (objective methods)

2.2.2.1 Measures of vascular disorders

Vibration-related vascular symptoms (termed VWF) are for more than 100 years a well-known and observed clinical manifestations of HAVS. These symptoms can be reflected by the weakening in peripheral circulation, such as the reductions in the digital blood flow velocity, blood pressure and skin temperature.

A number of studies have been published regarding the finger skin temperature (FST) test to assess the vascular function affected by vibration over the years (Voelter-Mahlknecht et al. 2006, Sakakibara et al. 2002, ISO 2005). Among the objective diagnostic methods, FST is easy to operate, mainly based on the measurement of the change in the temperature of the skin of the finger after cold provocation. However, the diagnostic validity of this technique suffers from questioning as there is no agreement on the quantitative standards. With different temperatures of the cold water, durations of the immersion and other test conditions, the reported sensitivities and specificities fluctuate over a considerable range (24-100% and 52-100% separately) in the white-finger cases (Harada and Mahbub 2008).

Finger rewarming time testing is also FST-based, working by measuring the time taken for recovering finger temperature by 4°C after immersion in cold water (Lindsell and Griffin 1998). Whether the recovery takes longer than 300s can indicate a case with or without VWF (Ye and Griffin 2016a). It is worth mentioning that due to the lack of guidance in grading symptoms, say, the whiteness scores (Lindsell and Griffin 1998, Ekenvall and Lindblad 1986), the extent of the vascular damage cannot be refined for diagnosis during this test.

Another frequently used technique for assessing the detection of vascular injuries should be finger systolic blood pressure (FSBP) testing (Harada and Mahbub 2008, Ye and Griffin 2016a). FSBP tests have better diagnostic capability than measurement of FST or finger rewarming time considering that FSBP provides better consistency for experimental conditions and test criteria. Moreover, reductions in FST and rewarming time after local cooling is susceptible to room temperature which is difficult to control while percentage changes in FSBP (%FSBP) are not influenced (Ye and Griffin 2017). Further studies have shown that the %FSBP can help in the staging of the severity of vibration-induced white fingers and make development predictions (Bovenzi et al. 2005, Bovenzi et al. 2008).

Laser Doppler techniques have also been applied for several years, which function by projecting a laser beam onto the surface of vascularised tissues and detecting the frequency shift of light to measure superficial blood flow velocity and other blood vessel characteristics. This technology is

reported to be useful to decide on an abnormality in vascular functions and that transposed to the differential diagnosis of HAVS. The published measures in this area involve laser Doppler flowmetry (Stoyneva 2004, Ziegler et al. 2004), laser Doppler anemometry (Stoyneva 2004, Ziegler et al. 2004), laser Doppler perfusion imager (Terada et al. 2007, Miyai et al. 2005) and laser Doppler ultrasonography (Lee et al. 2006), whilst the last one distinguishes between different groups of Raynaud's phenomenon not including VWF.

Vibration-affected populations are suggested to receive multiple testing approaches for accurate diagnostic purposes. In addition to the technologies mentioned above, conventional methods include self-reporting of symptoms and morbidity that they experience and visual witnessing of blanching by which an abnormal vascular response can be intuitively detected in comparison with colour charts (Negro et al. 2008, Youakim 2008). Novel techniques such as photoplethysmography (Harada 2011, Dyszkiewicz and Tendera 2006) looking at the changes in blood volume in the microvascular bed of tissue have been proven to be highly specific and sensitive. Gene expression from blood samples is also being developed as a novel way of investigating vascular function (Maeda et al. 2008, Krajnak and Waugh 2018).

2.2.2.2 Measures of neurological disorders

Neurological symptoms are mainly reflected in the reduced sensitivity, speed or response strength to external stimuli, most commonly, the vibration, temperature and mechanical press.

Vibration perception threshold testing (VPT) and thermal perception threshold testing (TPT) are two common test methods used to evaluate the abnormality in the sensorineural component of HAVS (Dupuis 1996, Gemne et al. 1995). Testing objects of these two methods are generally complementary. VPT is looking at the larger myelinated nerve fibres and TPT mainly assesses smaller ones and unmyelinated ones. Mechanoreceptors and temperature receptors are separately tested by VPT and TPT as well. Neither of them can be replaced for diagnosing nerve function though there is some correlation between them (McGeoch et al. 2004). In addition, both the vibration threshold and hot threshold show an increase under the stimulation of hand-arm vibration but are easily affected by various covariates and test methodologies, leading to insufficient sensitivity and specificity (Lundström 2002). It is recommended to apply these two quantitative sensory testing (QST) to HAVS assessment in association with other techniques.

Current perception threshold (CPT) testing is a neuro-selective technique (also a kind of QST), working by delivering a controlled electrical stimulus to elicit responses from peripheral nerves and evaluate the sensory processing (Katims et al. 1986). By performing at three different frequencies (5, 250, and 2000 Hz), small unmyelinated fibres, medium and large-sized myelinated nerve fibres are activated respectively, which allows for full characterisation of vibration-induced nerve

damage. The mapping of the distribution of peripheral neuropathy can also be obtained as the stimulating electrodes are portable enough to be attached to numerous sites of the skin.

Besides QST, nerve conduction studies (NCS) are widely used for the evaluation of nerve function. However, there are limited findings related to the usefulness of NCS in detecting HAVS. The measurement of the velocity of nerve conduction is mediated by large myelinated nerve fibres rather than receptors. As a result, this technology cannot serve as an early indicator of damage for which smaller nerve fibres are likely to be affected. Recently, NCS show some promise in identifying the presence of HAVS in multiple parts of the hand, such as the median, radial and ulnar nerves (Hirata and Sakakibara 2007). Moreover, careful control of body skin temperature is believed to aid in the differential diagnosis of HAVS and other similar diseases, say, Carpal Tunnel Syndrome (Cherniack et al. 2008).

It is unlikely to replace other diagnostic techniques by CPT, but its portability and sensitivity for the high Stockholm sensorineural stage appear to be useful in rapid screening for the clinical testing of HAVS (Lander et al. 2007, Kurozawa et al. 2010).

2.2.2.3 Measures of musculoskeletal disorders

Musculoskeletal problems are common among workers occupationally using vibrating power tools. Other than being related to physiological pain and perceived disability, it also consists of the reduction of manipulative dexterity in addition to muscle pathology, and damage in bone and joints. These aspects appear to be important indicators of musculoskeletal dysfunction (Poole and Mason 2007).

At present, studies on vibration exposure in relation to disorders in musculoskeletal system are still incomplete and worth further investigation. There are no definite severity scales of musculoskeletal diseases like vascular and neurological injuries (Gemne et al. 1987b, Brammer et al. 1987). Moreover, although tasks involving HAV are believed to be associated with musculoskeletal disorders, whether the disease necessarily comes from the vibration itself is lack enough evidence. Non-vibrating loadings such as static or dynamic loads (force) on joints, repetitions in hand movement and hand-arm posture also have an injury effect on the hand-arm system (Mason and Poole 2004, Chiari-Grisar et al. 2006).

Publications reporting the impact of vibration exposure on manipulative dexterity in HAVS cases constantly resort to novel techniques in which the Purdue pegboard testing method (Tiffin and Asher 1948) is the most widely used method. During the test, subjects are asked to move the coins or pegs into holes as many as possible within a specified amount of time. The score will then be determined by the number of coins or pegs inside the hole. The aim of such a test is to investigate

the ability to manipulate small objects or execute simple instructions. Subjects without vibration history perform significantly better than HTV workers, ruling out the effect of age, smoking and varieties of tools (Rui et al. 2008). Moreover, it has been found in the experiment conducted by Francesca in 2008 that the Purdue pegboard test has better sensitivity than self-reports in detecting loss of precise manipulation and appears to be a good way to distinguish stages of the deterioration in manipulative dexterity (Lundström et al. 2008). A distinct limit is that there might be an increase in scores over time due to the learning effect.

A similar assessment of the impairment of manipulative dexterity can be done by means of the Red bean transfer test (Sakakibara et al. 2005) and Grip ability test (GAT) (Björk et al. 2007) which are documented to correlate well with the result of Purdue pegboard test and sensorineural disturbances.

Studies have shown that changes in muscles morphology (Necking et al. 2004) and muscle strength caused by hand-arm vibration might further result in a high risk of muscular dysfunction among affected workers (Necking et al. 2002, Strömberg et al. 1998). Measures of muscle strength are non-invasive and can be applied to different parts of the hand.

Grip strength. The weakening of muscle in the hand has been proven to significantly affect handgrip strength (Bovenzi et al. 1991, Färkkilä 1978, McGeoch and Gilmour 2000, Miyashita et al. 1983). As a result, the measurement of maximum grip strength has been identified as a useful indicator for detecting muscle injury over the years (Cederlund et al. 1999, Taylor et al. 1986, Cherniack et al. 1990, Cederlund et al. 2003). However, the excessive force exerted by the subjects during the test is likely to lead to unexpected safety issues. Besides, the grip strength is driven by both the large extrinsic muscle groups (e.g., the forearm) and the intrinsic small hand muscles whereas the contribution of the former is more than that of the latter. It is argued that the lesions within the intrinsic ones may be covered up.

Pinch strength. It is recommended to perform quantitative pinch measurements such as key, palmar and fingertip pinch to assess the changes in the key intrinsic hand muscle strength. Limited evidence suggests that this alternative measurement may be more sensitive to muscle pathology induced by vibration than the measurement of grip strength (Mason and Poole 2004).

Abduction of fingers. The radial abduction of the index finger is an observational measure proposed by Necking in 2003, aimed to measure the isolated intrinsic muscle strength and exclude the effect of extrinsic muscle activities (Necking et al. 2003). The study concluded that the decline in the ability to perform index finger radial abduction can characterise intrinsic muscular dysfunction, which, along with the sensorineural component of HAVS, leads to the reduction in manipulative skills.

2.2.2.4 Measures of bones and joints disorders

The understanding of the effects on both bones and joints has not been deepened in recent years. Injuries affecting bone in the hands were reported to be osteoporosis and cysts (Poole and Mason 2007, Changulani et al. 2008) and the joints were osteoporosis in the wrist, elbow and shoulders (Hagberg 2002). But there is some inconsistency among studies dealing with the diagnosis of vibration-induced bone and joint diseases (Hagberg 2002, Suzuki et al. 1978, Lawrence 1955). It is widely admitted that repetitive shocks capable of transmitting strong energy to the hand-arm system seem to be a strong determinant contributing to the bone and joint dysfunction when the general model for injuries is considered (Cederlund et al. 2007).

2.2.3 Exclusive and differential diagnosis

The contribution of HAV to specific pathological changes or lack of function is still unclear. There are several additional factors likely to influence the effects of human exposure to HAV in working conditions as specified in Annex D of ISO standard 5349-1:2001 (ISO 2001a). The multitude of interactions and modifiers make defining a case of HAVS a challenge. Given the similarity in the signs and symptoms, problems reported in HAVS can be the result of a range of alternative disorders including Carpal Tunnel Syndrome (CTS), Thoracic outlet syndrome (TOS), Hypothenar hammer (HH), Primary Raynaud's phenomenon, etc (Mandic-Rajcevic et al. 2017). The other difficulty is highlighted by the prevalence of other diseases that occurred in vibration-exposed individuals. Problems that always co-exist with HAVS may bring on misdiagnosis of HAVS. Technologies and helpful information regarding the differential HAVS diagnosis are as follows:

- Electro diagnostics including nerve conduction studies can be useful in the diagnosis of TOS (McGillicuddy 2004), and the neurosensory component of HAVS (Burke et al. 2005, Ayse et al. 2007).
- Doppler techniques are able to determine HH (de Walle Van et al. 1998).
- The iontophoretic injection of chemicals help distinguish HAVS from Primary Raynaud's phenomenon (Dowd et al. 1998, Goldsmith et al. 1994).

Self-reports can exclude other causes of the symptoms related to HAVS based on occupational experience and health history.

2.3 Vascular effects and influencing factors

As mentioned above, the chronic adverse effects of HAV are reflected in the vascular, neurological, muscular, skeletal, and other aspects. Epidemiological studies of follow-up chronic cases alone cannot unravel the pathophysiological mechanisms involved in the development of HAVS.

By studying the short-term responses to HAV, factors, particularly the modifiable ones, that trigger such responses can be identified and their contributions can be evaluated. This knowledge helps to figure out the mechanisms through which HAV may cause long-term harm.

The following part will then also have a look at the acute effects of HAV in healthy people without vibration history, from the standpoint of preventing chronic symptoms. The vascular response here is also one of the most prominent acute effects and needs further research. Therefore, acute change in circulatory disturbances in the fingers and adjacent areas to HAV is being reviewed and discussed for effective evaluations of exposures, the predictability of symptoms and potential mechanisms of injuries.

2.3.1 Affecting factors: vibration

Human response to HAV is characterised by three aspects: the mechanism of the human body, localised vibration source, and the human's reception and physiological reaction to vibration. Vibration is the only external factor among the three above, referring to the reciprocating motion in a particular area around the fingers or the palm.

Studies on the acute effect of HAV exposure in healthy subjects have found that HAV provokes vasospastic reactions in blood vessels (characterised by a reduction in FBF, FST, etc), with the degree of the response related to the frequency, amplitude, duration and direction of the vibration stimuli. The regulation of the nervous system is considered to be involved in the process, and digital vasculatures of both exposed and unexposed hands are affected by the vibration. After the cessation of HAV, the vasoconstriction will last a period which also depends on the characteristics of vibration during the exposure.

2.3.1.1 Frequency of the vibration

Based on the frequency, contact area, and induced effect, human responses to vibration can be categorised into three distinct types: motion sickness, whole-body vibration response and local vibration (mostly hand-transmitted vibration) response. The corresponding frequency ranges of the vibrations are below 1 Hz, 1 to 20 Hz and 8 to 1000 Hz, respectively.

Table 2-2 Vibration types and frequency ranges

Frequency	*Vibration action mode*	*Impact description*
below 1 Hz	motion sickness	Motion sickness is a common phenomenon of physical discomfort triggered by low-frequency movement. The response is characterised by a range of signs and symptoms, such as headache, lethargy, rogue and pale look, usually followed by nausea and repeated vomiting rapidly once the initial response is developed (Reason and Brand 1975, Golding 2016). The most sensitive frequency band for oscillation in any direction is between 0.2 and 0.4 Hz.
1 to 20 Hz	whole-body vibration	It is generally believed that low frequency (below 20 Hz) and large amplitude of whole-body vibration mainly affect vestibule and visceral organs. When the vibration frequency is consistent with the natural frequency of human organs, resonance can occur, which amplifies the vibration intensity, strengthens the vibration effect, and aggravates organ damage.
8 to 1000 Hz	local vibration (HAV included)	Local vibration with relatively low frequency and high intensity is closely related to the problems in the arm joint system, and can be accompanied by changes in the nerve and muscle system. While vibration from 30 Hz to 300 Hz leads to obvious damage in peripheral blood vessels and nerve functions (Govindaraju et al. 2006, Gailiūnienė et al. 2017); the high-frequency vibration above 300 Hz has a weaker contracture effect on blood vessels but has a greater impact on the nervous system (Griffin 2012).

above 1000 Hz	--	Vibration above 1000 Hz is difficult to be subjectively felt by the human body.

The different frequency bands with the main impacts on the human body are summarised in Table **2-2**. This does not imply that vibration in these frequency bands can only have adverse effects on the body. Indeed, a number of researches report the positive effects of vibration interventions with low magnitude and high frequency (Nakagami et al. 2007, Ichioka et al. 2011). In terms of local vascular effect, for example, frequencies within 20 Hz to 50 Hz found beneficial to enhancing blood microcirculation are used to accelerate local wound recovery (Yu et al. 2017, Lohman III et al. 2011, Maloney-Hinds et al. 2008). In our study, however, only situations applying for the vascular response of exposure to HAV responsible for the risk of HAVS are taken into consideration.

In order to quantify the contribution of each frequency to the relative hazard posed by HAV, the frequency weighting W_h was recommended in ISO 5349-1 by British Standards Institution in 2001 (ISO 2001a). The W_h weighting was largely dependent on the discomfort contours of HAV as a function of frequency based on the 8 to 1000 Hz frequency range (Miwa 1968). However, how discomfort caused by HAV depends on the frequency can only provide an approximate indication of a single subjective response. According to the investigation regarding short-term HAV exposure, frequencies greater than 63 Hz are responsible for more vasoconstriction and stronger vascular after-effect (e.g. longer recovery) than at lower frequencies with similar stimuli velocity at all frequencies (Griffin 2012), and W_h weighting overestimates the risk at low frequencies (16 Hz and 31.5 Hz) (Bovenzi et al. 2000, Bovenzi et al. 2006). Such differences are confirmed by previous epidemiological studies and experienced populations as well (Futatsuka et al. 1984, Bovenzi 1998). Furthermore, HAV mainly works in the limited frequency range: there is a rare increase in the weighted value on tools at frequencies greater than 400 Hz and little experimental evidence of their vascular effects. The frequency band of most interest regarding HAV should be around 20 Hz to 400 Hz as shown in Table **2-2**, considering the centre frequency of the main frequency band of many vibration workpieces is 63 Hz, 125 Hz or 250 Hz, which is easy to result in peripheral vascular damage.

As it became evident that W_h weighting was not applicable to account for the vascular risk posed by vibration at different frequencies, a supplementary method of ISO 5349-1 for assessing the risk of vascular disorders was released in ISO/TR 18570:2017 and new frequency weighting W_p was put forward. W_p weighting extends the range of large weights to 20 - 400 Hz and is derived from biodynamic models characterizing vibration transmitted to the hand-arm system included in ISO 10068:2012, as well as from the epidemiological evidence for trial frequency weightings (Dong et al. 2012, Tominaga 2005, Bovenzi 2012, Pitts et al. 2012, Brammer and Pitts 2012). Compared with

W_h, W_p weighting is more compatible with previous studies and provides a better prediction for the risk of vascular disorders under rather high- or low-frequency HAV, but the actual impact over the full range is still worth further discussion. The comparison of frequency weighting curves W_p and W_h is given in Figure **2-3**.

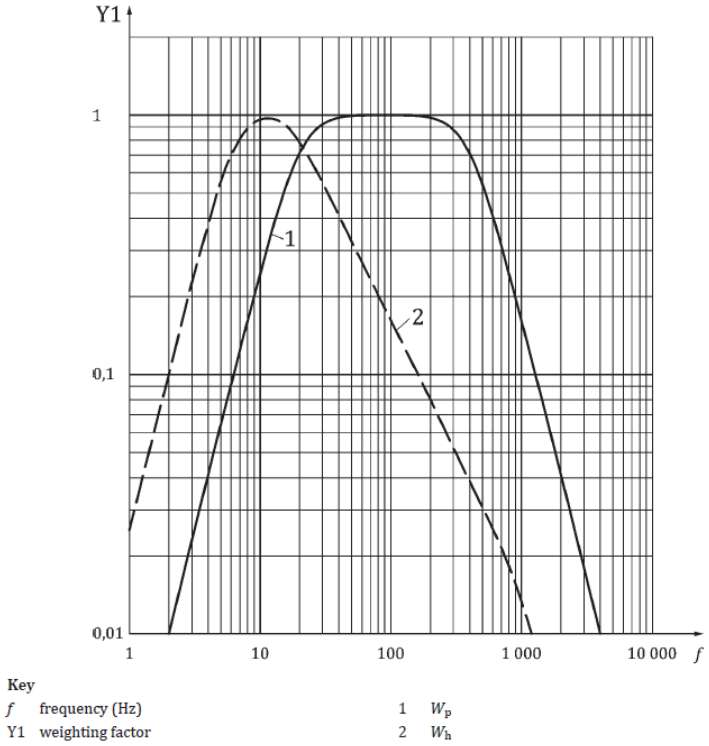


Figure 2-3 Comparison of frequency weightings W_p and W_h (ISO/TR 18570:2017).

The frequency range with a higher weighting factor covered by W_p weighting is above about 40 Hz, at which vascular injury and nerve injury are likely to be triggered as mentioned in above. After transmitted into the hand-arm system, vibration is absorbed by the soft tissues, and has the potential to cause vasoconstrictor reflex with additional damage to sensory and motor nerves affecting vaso-regulation. This suggests the possibility that there should be a close association between the vascular and neurological effects of HAV.

To our knowledge, vibration exposure is related to the release of some specific compounds like nitric oxide (able to widen blood vessels and stimulate the release of hormones) (Nakagami et al. 2007, Ichioka et al. 2011, Sackner et al. 2005, Napoli et al. 2006) and activation of neural reflex activity in the way that peripheral circulation can be regulated (Ye and Griffin 2011b, Thompson and Griffin 2009, Bovenzi et al. 1995a). There is also evidence that vascular changes are correlated with tactile sensation. According to previous studies, the Pacinian corpuscle (PC) responds primarily to vibratory stimuli at higher frequencies (~40 to 400 Hz) (Verrillo and Gescheider 1975, Verrillo 1966b), which is similar to that of vascular response. The Pacinian channel mediates the perception of vibration near-threshold, with the reduction in FBF starting to occur when vibration is

perceptible (Thompson and Griffin 2009, Bovenzi et al. 1999, Ye and Griffin 2013). While at frequencies below 40 Hz, the vibrotactile sensation is mediated by the non-Pacinian system at the threshold and vasoconstriction does not appear at low levels of HAV (Gescheider et al. 1978, Thompson and Griffin 2009, Gescheider et al. 2002). Thus, the involvement of mechanoreceptors mediating blood flow regulation might partially explain the dependence of the trigger of the vascular response on the vibration frequency. In recent years, the extent of reduction in FBF has also been reported to be related to vibrotactile sensitivity, that the HAV-induced vasoconstriction is more pronounced in those with lower vibrotactile perception thresholds (Ye and Griffin 2011b, Ye and Griffin 2014).

For various experimental studies (including those for patients with VWF or healthy groups), 125 Hz is the preferred frequency to measure the changes in local circulation in fingers (Hyvärinen et al. 1973, Thompson and Griffin 2009, Ye and Griffin 2011b). 125 Hz is not only the dominant frequency for vibration of many powered hand-held tools, but also falls in the frequency region where the PC (abundant in fingers as described in section 2.1) is sensitive to vibration. Thus, HAV is expected to affect fingers but of less stringent effects elsewhere, which will be confirmed in the study of contact location effect later in this review.

2.3.1.2 Magnitude of the vibration

Displacement, velocity, and acceleration are introduced to describe the strength of the vibration stimuli and measure the extent to which the human body perceives vibration. Generally, single-frequency input signals were employed, allowing for connecting and comparing values between different studies.

In the early days, displacement (i.e., amplitude) was frequently used as a measure of vibration exposure. FBF in healthy subjects was observed to significantly decrease with the HAV displacement increasing from 0.125 mm to 1.0 mm at 80 Hz (Welsh 1980), though the vibration intensity employed here was much lower than those provided by tools, considering the safety limit. A study by Pyykkö et al examined that, for both healthy subjects and lumberjacks who were habitual users of hand-held tools, the vasospasm was more likely to be triggered with higher amplitude (peak to peak displacement) 530 μm than low amplitude within 160-265 μm at 125 Hz using piezoelectric or photoelectric plethysmography (Pyykko 1982). This implies that healthy subjects and patients respond to HAV magnitude in a similar way. In sight of all the above, studying the acute exposure to vibration with moderate intensity in healthy subjects can contribute to investigating the dependence of vascular response on the HAV magnitude.

On further studying the acute digital circulatory effects of magnitude both during and after the exposure to HAV, Egan et al measured the FBF and FST in healthy subjects whose right hands were

exposed to low- or high-intensity vibration of pneumatic chisels for two minutes (Egan et al. 1996). It has been found that there are reductions in FBF which depends on the vibration magnitude but no change in FST, and after cessation of vibration, vasoconstriction continues and the post-effect is significant compared to pre-experiment. Also, recovery after exposure to high-intensity HAV turns out to be more difficult. Similar results are reported by Bovenzi et al with the magnitude of the exposure more precisely quantified over 5.5 m/s^2 to 62 m/s^2 at 125 Hz (Bovenzi et al. 1999). In addition, it can be seen that acceleration has often been used lately to characterise the stimuli magnitude and the extent of response has been found related to the level of acceleration (e.g., the W_h frequency weighted curve is derived from the equivalent comfort curve against acceleration). In addition, multiple types of instruments are available for measuring acceleration, by which the velocity and displacement of HAV can also be given. Table **2-3** provides an overview of the amplitude (acceleration) ranges for common vibrating workpieces.

Table 2-3 Amplitude ranges of typical vibrating workpieces

Vibrating workpieces	**Amplitude Range (m/s^2)**
Plate Compactor	2 - 10
Vibratory Roller	5 - 25
Vibrating Surface Grinder	10 - 30
Handheld Electric Hammer Drill	10 - 50
Jackhammer	20 - 50
Pneumatic Tamper	30 - 60
Pneumatic Chipping Hammer	20 - 70
Rotary Vibrating Screen	20 - 80
Vibrating Sieve	20 - 100

With the same vibration frequency, the greater the stimuli intensity (displacement, acceleration), the greater the powerful vasoconstrictor effects on blood vessels. Subsequently, more attention is being paid to the function between stimuli magnitude and human responses. Suppose that the magnitude of acute exposure increases by a factor of two, it is assumed that the reduction in digital circulation would also double. Previous experiments indicate that the vasospasms start to be triggered by vibration with an intensity that runs parallelly 20 dB above the sensation levels at different frequencies (Hyvärinen et al. 1973). Moreover, the spastic reaction is most potent around 125 Hz, at which the FBF decreases almost linearly with the magnitude increment (Welsh 2003).

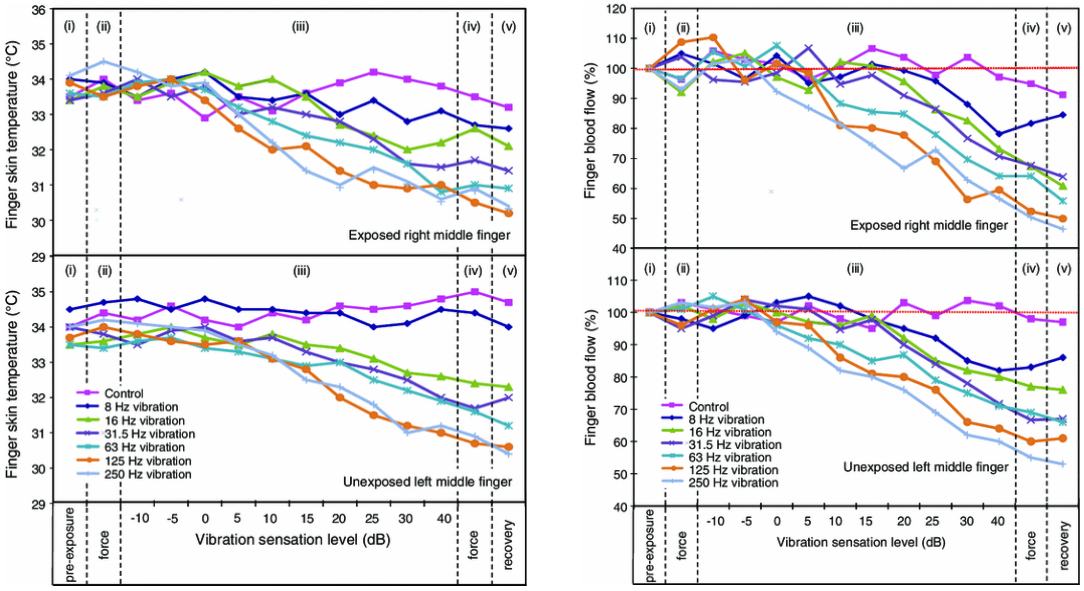


Figure 2-4 Comparison of median FST and %FBF measured 14 healthy subjects in right exposed and left unexposed fingers between the control condition and six exposure conditions with HAV applied on the right thenar eminence (Ye and Griffin 2014).

However, more and more studies have revealed that the effects of magnitude are non-linear, partly because the human body itself is a non-linear system that the transmissibility of vibration may vary between different magnitudes. Also, the dependence of vasospastic reactions on magnitude differs according to other factors, such as frequencies and duration of vibration exposure. This has been proven in some combination-effect studies, for example, there is evidence that the digital vessels are more affected by greater vibration magnitude at different frequencies, but the responses do not vary in a linear way, either during or after the exposure (Bovenzi et al. 2000, Bovenzi et al. 2006, Ye and Griffin 2014). Vibration at relatively high frequencies (125, 250 and 315 Hz) results in more reduction in FBF (Thompson and Griffin 2009). Figure **2-4** shows the acute change in digital circulation applied with different combinations of vibration frequencies and magnitudes, in which the alterations in both FST and FBF are correlated with the level of vibration stimulation besides the frequency. In general, the extent of the acute vascular response of magnitude is related to frequency, duration and many other variables: there should be complex interactions between them. Current frequency weightings, as well as duration weightings, are based on the premise that the influence of HAV is an independent function of vibration magnitude (Bovenzi et al. 2000).

2.3.1.3 Duration of the vibration

A proper amount of local or whole-body vibration is of benefit to physical and mental health. It can enhance muscle activity (Bosco et al. 1999, Roelants et al. 2006), relieve fatigue and pain, promote metabolism (Rittweger et al. 2002), improve tissue nutrition (Di Loreto et al. 2004, Goto and

Takamatsu 2005) and accelerate wound healing. Being aware of the positive impact of vibration on the human body, novel ideas of treating vibration as an alternative training mechanism to traditional exercise came about decades ago, and handfuls of studies have begun to investigate the use of vibration to help populations with poor peripheral circulation problems in their upper limbs (Maloney-Hinds et al. 2008).

While under the condition of production, the vibration exposed by workers is characterised by high intensity and long time, which may lead to adverse health effects on the body and even cause diseases. The occurrence of white finger disease is closely related to the adverse reactions on nerves and microvasculature induced by prolonged HAV (Nakagami et al. 2007). The international standard ISO 5349 was issued in 1986 to specify the certain vibration dose that should not be exceeded, in which the Exposure Duration of HAV refers to the trigger time during which the hand is actually subjected to vibration. The evaluation of continuous vibration correlates with the influence of stimuli intensity, whereby in case of large amplitude, the contact time should be shorten to meet the same "energy equivalent" acceleration magnitude.

The studies on acute vibration response employ limited exposure time, but the contribution of duration to acute changes in digital circulation could also be observed. It is found compared to pre-exposure, HAV induces notable reductions in FBF and increases in vascular resistance, the response being most significant in the first minute after applying stimulation to the fingers (Bovenzi et al. 2001). By varying the duration, Bovenzi et al. has found that the vasospastic reactions are not abolished by repeated bouts of HAV, and there is a continued decrease in FBF with an increase in exposure time.

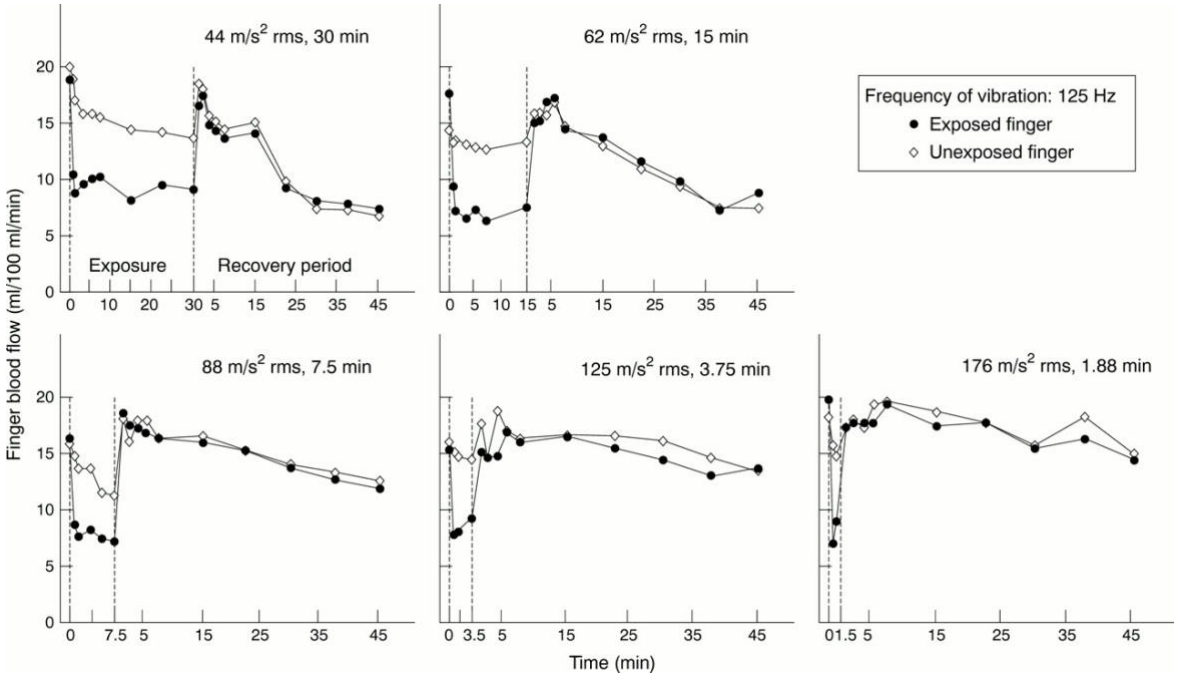


Figure 2-5 Comparison of mean FBF measured in 10 subjects between conditions with different HAV magnitudes and durations at 125 Hz (Bovenzi et al. 2001).

Vascular response after HAV exposure seems to be a separate phenomenon different from that during exposure. Immediately after the cessation of vibration, transient vasodilation and increases in the blood flow can be frequently observed if shortening the sampling interval on a short period of time after the exposure (Bovenzi et al. 1998, Bovenzi et al. 2001). This may result from an acute reaction symptom following tissue ischemia that the blood returns to the vessels suddenly (reactive hyperaemia), mainly regulated via the release of NO or neuropeptides due to the HAV acting on the vasculature (Sackner et al. 2005, Napoli et al. 2006, Nakagami et al. 2007). Over the whole recovery period, vasoconstriction remains for a period as shown in Figure **2-5**. The persisting post-effects also depend on the duration of the prior HAV exposure, with greater vasoconstrictor effects and delayed recovery after longer durations of exposure (Bovenzi et al. 2001).

2.3.1.4 Direction of the vibration

The coordinate system allows for the decomposition and analysis of vibration direction. For whole-body vibration, there are six dynamical degrees of freedom: three for translation and three for rotation. The x, y and z axes stand for the fore-and-aft, lateral (left-and-right) and vertical (up-and-down) directions; the roll, pitch and yaw respectively refer to three directions of rotation. When it comes to hand-transmitted vibration, the coordinate system is built with respect to the hand of the human, which is known as the biodynamic (BD) coordinate system as shown in Figure **2-6** (ISO 1997, ISO 2001a). The x_h-axis passes through the palm (dorsal-to-ventral); the y_h-axis goes from the right of the palm to the left; the z_h-axis is parallel to the third metacarpal bone. Rotational vibration is rarely mentioned in the literature about HAV. It is sometimes difficult to fully align the accelerometers with the hand-arm system, thus a basicentric (BC) coordinate system has been adopted in standards and many studies with three orthogonal axes that share the same origin close to where the tool is grasped by the hand (ISO 1997, ISO 2001a, Wasserman 1996, Dong et al. 2015).

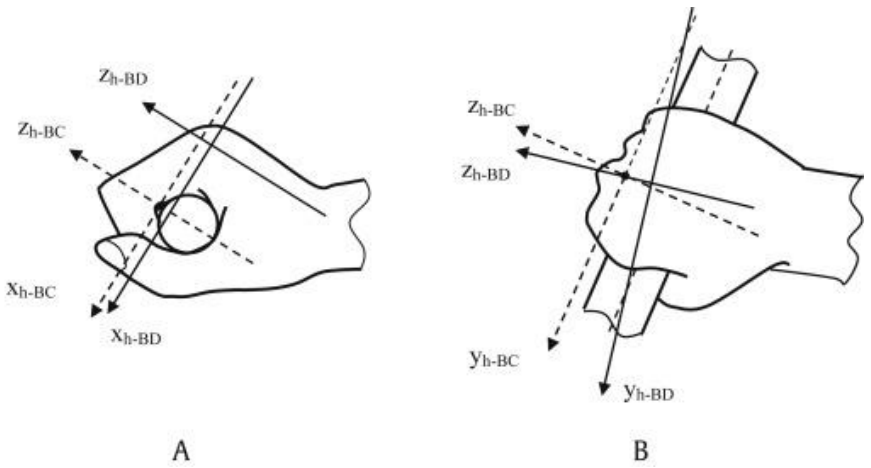


Figure 2-6 BD and BC hand coordinate systems standardised for measuring hand force and vibration (Dong et al. 2015).

During production activities, the vibration level that tool operators are exposed to varies in each direction (Goglia et al. 2006, Forouharmajd and Nassiri 2011), and the vibration effect is also direction specific. So far, there are few studies investigating whether the circulatory effects depend on the excitation direction. The influence of HAV direction is mainly assessed from the quantity of transferred energy or the absorbed power.

In Bylund and Burström's experiment, the random HAV signal is applied over the frequency range of 4-2000 Hz in two orthogonal directions, x_h and z_h, achieved by altering the subjects' position (either a sitting position or an upright body position) with the arm stretched out (Bylund and Burström 2003). The HAV energy absorption of the z_h direction turns out to be higher than that of x_h direction. With regards to the energy transfer in all three directions, the exposures in Besa's study consist of a sine sweep ranging from 1 to 700 Hz in each axis (Besa et al. 2007). It is found that below 185 Hz, the absorption of HAV energy from x_h or y_h excitation is lower than z_h, while above 185 Hz, x_h exhibits relatively higher absorption. The result is partly consistent with the previous finding from Mishoe and Suggs in which the vibration input is suggested to be in the x_h direction (vertical) under 100 Hz and in the transverse direction above 100 Hz to minimise the energy dissipation (Mishoe and Suggs 1977). Recently, Welcome et al. have compared the transmissibility in the hand-arm system with stimuli excited in three directions using a 3D laser vibrometer. There seem to be different indications that the peak transmissibility for y_h axis is generally the highest, regardless of the different resonance frequency bands of the wrist and hand dorsum (30-40 Hz) and fingers (above 100 Hz) (Welcome et al. 2015).

On the basis of the experimental results, several proposals of frequency filter and energetic summation with axis weighting have been put forward to better represent the direction effects (Stelling and Dupuis 1996, Besa et al. 2007). As suggested, a new frequency weighting in three directions for HAV measurement should be derived instead of applying only a single frequency weighting for all the axes in the current standard (ISO 2001a). Moreover, the effect of stimuli direction on digital hemodynamics remains to be studied.

2.3.2 Biodynamic factors (force included)

2.3.2.1 Contact interfaces

Contact area. The contact interface between skin and vibrator cannot be neglected as a factor influencing the effect of HAV. For a localised vibration source, the contact area is limited, and the contact condition differs according to the shape of the vibrating object and the habit of exertion between individuals. Experimental studies on the effect of contact area tend to allow the hand of the participant, in general, to rest on the vibrating platform (palm down) at the heart level, whilst the fingers of the exposed hand are suspended in the air.

With HAV of 125-Hz applied to the right thenar eminence, Ye and Griffin compare the loss in FBF between exposure to two different sizes of contactors (3 mm and 6 mm probes) at the same sensory level (15 dB above the threshold for each probe) (Ye and Griffin 2013). The result showed a reduction in vibrotactile and a potent increment in vasoconstriction by doubling the diameter of the contact area. The produce of 'spatial summation' mediated by the Pacinian channel can be invoked to explain the effect of the area exposed to vibration, as the increment in Pacinian activation is responsible for provoking stronger vibration perception and greater reduction in FBF with increased contact area (Verrillo 1966a). Experimental data from Krajnak et al. tested on tissue samples of rat tail further confirm that greater area of contact gives rise to increased vibration level transmissibility and elevated factors correlated with peripheral vascular and sensorineural remodelling and dysfunction, which is consistent with in vitro studies of humans (Krajnak et al. 2018).

Contact location. The acute vascular response of HAV is not restricted to the contact location experiencing the vibration. As early as the 1990s, it has been found that both vibrated and non-vibrated hands respond to the vibration stimuli, and the phenomenon are believed to be driven by two different mechanisms.

In the measurement of the blood flow before and after vibration using strain gauge plethysmography, prompt vascular dilation appears in the exposed finger immediately after exposure, probably arising from the locally mediated mechanisms by the relaxation of vibration on the smooth muscles of the vascular wall; in contrast, the decrease in FBF in both the exposed and the unexposed fingers during recovery is due to the vibration-induced vasospastic reactions and regulation through a central sympathetic reflex mechanism (Bovenzi et al. 1995a, Greenstein and Kester 1992). Many experimental studies have also provided evidence that during the exposure, the HAV provokes digital vasoconstriction in both the vibrated (ipsilateral) hand and the non-vibrated (contralateral) hand, supporting that a central sympathetic response activated by mechanoreceptors contributes to the acute digital vascular response (Egan et al. 1996, Bovenzi et al. 2000, Griffin et al. 2006). Understandably, the response of the vibration-exposed fingers is more pronounced than that in the unexposed hand (Bovenzi et al. 1998, Bovenzi et al. 1999, Bovenzi et al. 2000, Bovenzi et al. 2006). Both hands exhibit more loss in digital blood flow as the stimuli magnitude on the right hand increases (Bovenzi et al. 2006, Ye and Griffin 2009). In view of the similar pattern of digital circulatory functions in both hands, measurement of vasoconstriction can be taken on the contralateral hand when it is difficult to monitor the vibrated fingers (Ye and Griffin 2011a).

It should be noted that, the vibration might be applied on either the palm or the fingers, but little attention has been paid to the possible difference between these two contact locations. The

findings from Ye and Griffin report the variations in vasoconstriction with the application of vibration to three contact locations (right index finger, right thenar eminence, and left thenar eminence) at 125 Hz (Ye and Griffin 2016b). It is found that digital blood flows of both hands are most affected by the vibration on the vibrated fingers in the right hand. Since fingers have greater sensitivity to vibration compared with thenar eminence, it is suggested that there is a strong association between locations of excitation with vibrotactile perception thresholds and corresponding vascular response. Apart from that, it cannot be ruled out that the relative movement between substructures of the hand may also contribute to the differences. When it comes to the evaluation of the anti-vibration effect of gloves, a striking finding is that there is attenuation in the palm, but the vibration transmissibility to fingers increases instead of decreasing, which indicates the dependence of vibration attenuation on location.

2.3.2.2 Applied force

Force-induced static muscular load can compress tissues, resulting in increased pressure in muscle compartments, as well as impeded lymphatic drainage and venous return.

Meanwhile, how hard a subject grasps the vibrating piece contributes to the amount of vibration power entering the hands. The force applied, therefore, is another crucial factor to consider in assessing the HAV exposure, in addition to the contact area.

Quite a few studies have encompassed the influence of contact force on the FBF, for the most part, with hands pressing down on the contactor. Some results have been obtained as to whether the blood flow is affected by the applied force alone and whether it is affected by the combination of force and vibration. Bovenzi et al. point out that even modest levels of force (2 N or 5 N) without HAV can lead to a reduction in FBF on the exposed fingers but no change in other fingers. The unilateral effect is considered to be the result of the constriction of local digital vasculature. When applying the HAV, the contact force interacted with the vibration to provoke additional vasoconstriction in FBF, which is not limited to the exposed fingers (Bovenzi et al. 2006). Another study conducted by Griffin et al. find that a force of 20 N on the palm of the right hand is capable of altering the finger circulation in both the ipsilateral fingers and contralateral fingers (Griffin et al. 2006). Some research comes to a different conclusion that exposure to force alone would not lead

to any change in the FBF, though the forces applied are relatively small (around 2 N) (Thompson and Griffin 2009, Ye and Griffin 2009).

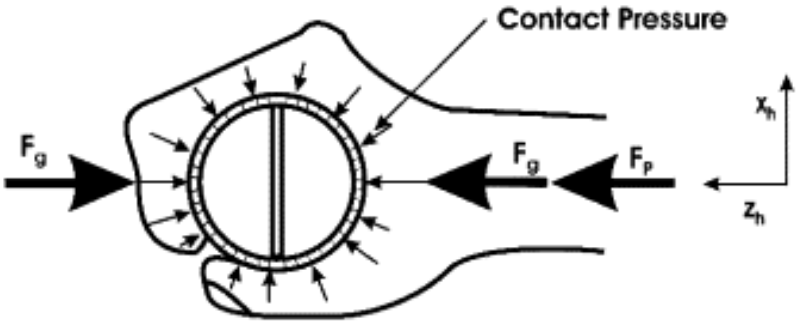


Figure 2-7 Illustration of hand forces with a handgrip posture (Welcome et al. 2004).

However, these conclusions are not applicable in relation to blood flow response with the actual contact force. Most hand-held vibration tools are equipped with a handle structure, and the contact force exerted on it should be a combination of grip force and push force (also known as feed force). It can be seen from Figure **2-7** that the distribution of interface stress over the contact area is complex, as the grip forces F_g in pairs occur in the opposite directions and push force (or pull force) F_p acts along the z_h direction. An investigation from Welcome et al. proposes that the contact force can be characterised as a function of grip force, push force and handle size, in which the contribution of grip force is greater than that of the push force (Welcome et al. 2004). Moreover, the relevant biodynamics research find that grasping mainly affects the dynamic response of the forearm and pushing acts on the entire hand-arm system (Adewusi et al. 2010). Considering grasping a power hand tool, the amount of force exertion should be large enough in order to avoid sliding (Radwin et al. 1987). Although it is difficult to measure the vascular response of fingers on the handle, how the circulatory effect of vibration will be influenced by the presence of such kind of applied force could be an 'issue' worth further investigation.

2.3.3 Other objective factors

2.3.3.1 Individual variability

The vascular response of the hand-arm system to HAV varies among individuals. The possible influential differences within or between the human body are listed in Table **2-4**. Effects of these intrinsic variables are believed to exist in developing HAVS, but the underlying progress remains almost unknown.

Table 2-4 Intrinsic variables influencing the vascular response

Intra-subject variability	**Inter-subject variability:**
body posture	age
hand/finger posture	gender
hand position	body size and mass
hand orientation	body dynamic response
ingestion	body temperature
	medical history (smoking, etc)
	fitness (maximal voluntary contraction)
	habit of exertion

For exposure to acute vibration, the response with respect to intra-subject variability is relatively easy to study, for example, by altering body postures (sitting, standing or recumbent). A study from Adewusi et al. shows that vibration below 25 Hz is prone to be transmitted to the upper arm with fully extended-arm postures, whereas vibration power at frequencies above 25 Hz can be more effectively absorbed in the hand-arm system with extended-arm posture compared to bent-arm posture (Adewusi et al. 2010). The hand-arm posture has a great influence on the nature of vibration attenuation, though there are few studies taking this factor into consideration, partly because it is almost impossible to be exposed to HAV without changing hand-arm posture and position.

The correlation between digital circulation and inter-subject variability is also notable. Bovenzi et al. test on healthy individuals and report an association between large differences in FBF and finger volume and age (Bovenzi et al. 1995b). Body size and mass are suggested to explain the large differences in digital blood flow in a study by Ye and Griffin (Ye and Griffin 2011a). The difference between genders is reflected in their sensitivity to vibration as some frequency bands of vibration are perceived to be stronger for women (Neely et al. 2001), and the grip strength is generally greater in men than that in women (Haward and Griffin 2002), which may be related to altered digital blood flow. It is no doubt that medical history and habits have a bearing on the severity of human response to acute vibration. The smoking effect is examined by Morecraft et al. that there is an increment in finger vascular resistance in both pre-smoke and post-smoke measurements and volumetric flow is significantly affected (Morecraft et al. 1994). Individuals with medical histories of diabetes, cardiovascular disease or neurological problems are at higher risk of developing HAVS. It follows that the health status and any medical treatment of subjects should not be ignored when considering the acute or chronic adverse effects of HAV.

2.3.3.2 Skin temperature and room temperature

The temperature of blood within the vessels is 38° C, around one degree higher than body temperature. Circulating blood ensures that the body temperature is maintained at an ideal level, by absorbing or releasing heat from plasma and changing the speed of blood flow. When blood vessels expand, volumetric flow increases and heat exchange is completed quickly, which will give off excess heat. When the ambient temperature drops, vessels will contract to minimise heat loss. Therefore, variations in workplace temperature and damp or windy conditions can alter the peripheral circulation.

In a series of cold provocation tests to assess the dependence of FST and digital regulation on environmental temperature, an elegant demonstration is made by Harada et al.: room temperature varying 1 ° C (within the range between 15 ° C and 25 ° C) will result in a temperature change of more than 1 ° C in the finger skin before and after cold-stress tests (CST), and the FST during CST in summer is significantly highest in all seasons (Harada et al. 1998). This result reveals that FST is strongly affected by indoor temperature as well as seasonal conditions. There is also evidence that FST and FBF in those with VWF tend to be lower than that in controllers after the cold immersion, in which the FST shows a close correlation with the deep FBF (Mirbod et al. 1998). Another study is undertaken by Coughlin et al. using cold provocation thermography (CPT), demonstrating that the passive rewarming takes place after cooling, and that patients with Raynaud's phenomenon (RP) secondary to HAVS has a lower finger-tip temperature and finger-base temperature than healthy subjects during the course (Coughlin et al. 2001).

The effect of environment temperature has also been examined in acute HAV experiments. Mahbub et al. investigate how the room temperature influences the reactive hyperaemia in healthy subjects elicited by acute exposure to a vibrating handle (Mahbub et al. 2006). It discloses that the finger superficial vessels are dilated more effectively at a lower environmental temperature (15 ° C) than at a higher test temperature (30 ° C) immediately after the vibration ends. Further investigation has been carried out by Ye and Griffin to reveal the dependence of decreased blood circulation during HAV exposure on room temperature (Ye and Griffin 2011a). Greater vasoconstriction is observed at higher room temperature as HAV provokes a more significant absolute reduction in FBF and FST at 28°C than at 20°C, though the change in %FBF is similar with both temperatures. The results are illustrated in Figure **2-8**, it is seen that the FST and FBF are of different patterns under different room temperature conditions.

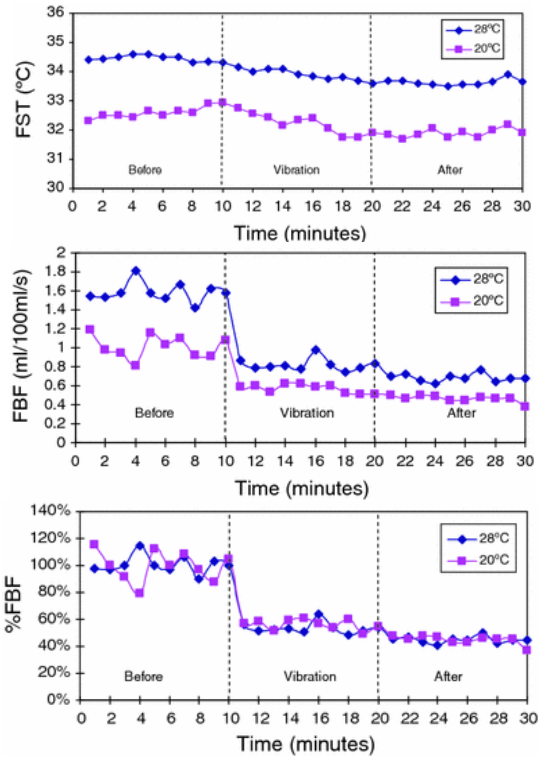


Figure 2-8 Comparison of median values of FST, FBF and %FBF between different room temperatures in a contralateral finger with right fingers exposed to a 125 Hz HAV (Ye and Griffin 2011a).

There remains uncertainty related to the role of FST in monitoring peripheral circulatory functions. It can be seen that in the cold provocation tests, FST does vary with the change of experimental temperature, and is more affected in those with VWF than in healthy people. It seems that FST is regulated as part of the blood flow system. However, when it comes to tests regarding exposure to HAV, there is no pronounced acute response in FST caused by vibration according to the previous studies. FST appears to be only sensitive to ambient temperature, suggesting FST is still a useful physiological parameter for characterizing the room temperature.

2.4 Neurological and musculoskeletal effects and influencing factors

2.4.1 Sensorineural response

2.4.1.1 Neural control of vibration response

The adverse symptoms of overexposure to HAV are often concomitant. Affected hands suffer from the loss of colouration, accompanied by persistent finger tingling and numbness, and these painful attacks would be at their most severe during chilly cold weather (Heaver et al. 2011, Seyring 1930).

It turns out that the incoming vibration could cut off the blood supply to the nerves, and would be followed by a throbbing sensation when the blood returns (Herrick 2005).

The lack of feeding and frequent vibratory stimulation of nerves would lead to the deterioration of hand function, not only reduced manual dexterity, but also a great loss of sense (Rui et al. 2008, Forouharmajd et al. 2017). As a crucial role in the somatosensory system, nerves are in charge of the sensation of the hand and the transmission of the signals to the brain. The functional neural network anatomy is complex, in which the mechanosensory function of the hand is attributed to mechanoreceptors located in the dermis and epidermis. The detection of vibratory sensation, for instance, is primarily mediated by a fast-adapting receptor known as Pacinian corpuscles (Quintero 1984, Lundström 1986, Verrillo and Gescheider 1975). And the receptors respond to temperature change are known as cold-sensitive thermoreceptors and warm-sensitive thermoreceptors.

It is documented that the ability to sense vibrations is temporarily impaired following HAV exposure (temporary threshold shift), thereby decreasing the awareness of the early warning signals (Lundström et al. 1999, Thonnard et al. 1997). The skin's perception of heat and cold is also weakened in response to the HAV (Nilsson et al. 2008, Ye and Griffin 2018). For healthy individuals, this temporary loss of sensation will soon disappear, but with prolonged exposure, the symptom is at risk of becoming permanent (Gerhardsson and Hagberg 2019, Nilsson et al. 2017). Thus quantitative sensory testing (QST) such as the test on vibrotactile perception threshold (VPT) and the test on thermotactile perception threshold (TPT) have been developed nowadays. They are standardised for the diagnosis of HAV-associated chronic peripheral neuropathy (Lindsell and Griffin 1998, ISO 2001b, Ye and Griffin 2018), as well as for the investigation of the dose-relationship between vibration and its acute sensorineural responses: the temporary threshold shifts (TTS) of vibrotactile perception and thermotactile perception (Löfgren et al. 2020, Burström et al. 2009, Shibata 2022).

2.4.1.2 Affecting factors

Stimulus frequency. The perception of vibration is frequency-dependent, since different frequencies excite different receptors responsible for vibration perception. The Pacinian channel (P channel), which primarily mediates vibration perception at frequencies ranging from 2 to 800 Hz, exhibits a U-shaped contour of displacement thresholds (Verrillo 1963, Gu 2010). It shows maximum sensitivity to displacement at around 200 to 300 Hz, with a slope of -12 dB per doubling of frequency within the range of 15 to 200 Hz. In comparison, the non-Pacinian (NP) I channel is involved in mediating vibration perception at lower frequencies, typically from 30 to 50 Hz (Gescheider et al. 2002). The variation in thermal threshold with changes in stimulus frequency has yielded different conclusions in previous studies. Hirosawa et al. reveal an increase in the

warmth threshold with an escalation in vibration level, reaching its maximum at 125 Hz among the tested frequencies (ranging from 32 Hz to 500 Hz). On the other hand, study from Burström et al. indicates that neither the frequency nor the duration of vibration stimuli has a notable effect on the sensation of cold or warmth (Burström et al. 2008).

Stimulus duration. The duration of the vibration stimulus plays a role in the acute sensorineural response to HAV. Temporal summation theory suggests that vibrotactile thresholds fall as stimulus duration rises (Gescheider 1976, Gescheider et al. 1999). However, the effect of stimulus duration varies depending on the specific sensory channel involved. For example, the P channel, which mediates vibration perception at around 200 Hz, exhibits temporal summation; whereas the NP I channel, which mediates vibration perception at about 30 Hz, does not demonstrate a significant influence of stimulus duration.

Contact area and location. Vibration sensation is influenced by the area and point of contact surface. In general, larger contact areas lead to increased sensitivity to vibration, particularly at frequencies above 40 Hz. This effect is attributed to spatial summation mediated by the Pacinian system (Verrillo 1963, Verrillo 1985, Morioka et al. 2008). Moreover, the location of contact also affects vibration thresholds, with fingertips being more sensitive to vibration compared to other areas on the glabrous skin of the hand (Lo¨fvenberg and Johansson 1984, Morioka and Griffin 2005). Limited research has been conducted regarding the influence of contact condition on the thermal threshold.

Contact force. The contact force exertion affects the sensation when triggered by small vibrations. Increasing the contact force can enhance the perceived magnitude of vibration. Thus the rest value of vibrotactile thresholds tends to decrease with more contact force being applied. This effect is more pronounced for the Pacinian system compared to the non-Pacinian system, indicating that force influences the sensation more when mediated by Pacinian receptors (Green and Craig 1974, Makous et al. 1996, Harada and Griffin 1991). Taking into account the force exerted by full hand contact during the exposure, as proposed by Thonnard, the forces might vary depending on the specific task when using vibrating tools (Thonnard et al. 1997). Research exploring the impact of force with a grasping posture has revealed that increased hand force may result in more temporary shifts in vibrotactile and thermotactile thresholds (Nishiyama et al. 1996, Maeda et al. 2007, Löfgren et al. 2020).

Skin temperature. The temperature of the skin has an effect on vibrotactile thresholds. Lower skin temperatures generally result in elevated vibration perception thresholds, especially at higher frequencies (Bolanowski and Verrillo 1982, Harazin et al. 2013). In contrast, a moderate

temperature range shows little variation in thresholds. While at temperatures above 35 °C, the sensitivity to vibration decreases, resulting in an increase in the thresholds.

Individual factors. Several individual factors may influence how nerve system responds to HAV. Gender, body size, and age are among the individual characteristics that may contribute to differences in vibration perception (Neely and Burström 2006, Skov et al. 1998, Wiles et al. 1991). These factors are involved in determining an individual's susceptibility and sensitivity to the effects of HAV.

2.4.1.3 Relationship between neurological and circulatory effects

As for the acute responses of the vascular and nervous systems to vibration, research indicates that both systems are likely affected together (Ye and Griffin 2011b). Notably, the factors influencing these responses tend to overlap, and the observed changes exhibit a consistent trend following vibration exposure. These findings suggest a possible correlation or mutual influence between the two systems.

Vascular alterations following vibration, such as vasoconstriction and tissue ischemia, may directly affect neural tissues, leading to altered neural function, impaired sensory perception, and diminished nerve conduction. Likewise, neural responses, including nerve compression or excitability, can impact vascular responses, leading to further changes in blood flow dynamics.

As a result, the combination of acute vascular and neural effects during vibration can lead to a complex interaction between the two systems where each component influences the other.

2.4.2 Musculoskeletal response

Unlike chronic effects, short-term musculoskeletal responses to HAV exposure are not significantly manifested in skeletal changes, and studies mainly focus on timely responses in muscles.

HAV may trigger involuntary muscle contractions, known as tonic vibration reflex (TVR) or increase in muscle activity (Eklund and Hagbarth 1966, Kihlberg et al. 1995, Masud et al. 2022). These contractions can result in muscle spasms or twitching, leading to discomfort or pain. At the same time, muscle fatigue may occur over time, which refers to a decline in muscle strength and endurance. Exposure to HAV requires continuous muscle activation to counteract the vibration and maintain grip or posture, which wears the muscles out. In the affected areas, there is also a possibility that immediate tissue damage may result from acute exposure to high-intensity HAV. The soft tissues, such as muscles, tendons, and blood vessels, may sustain microtrauma as a result of this injury.

Joint instability is another side effect of HAV, particularly in the fingers, wrists, and elbows. The dynamic loading caused by vibration may induce joint laxity or looseness, which limits the range of motion and functions.

The musculoskeletal system might be indirectly affected by the acute vascular changes brought on by HAV. Reduced blood flow and impaired tissue oxygenation may slow down the recovery and regeneration processes, contributing to muscle fatigue, pain and impaired muscle performance, and making the musculoskeletal tissues more susceptible to injury.

2.5 Modelling

2.5.1 Lumped parameter mechanical-equivalent modelling

The development of the modelling and animation of hand and fingers in accuracy and feasibility has been witnessed since the tendon pulley static model was first proposed in the 1960s (Landsmeer 1961).

On the one hand, there is an emerging trend in modelling aimed at tracking and capturing the movements of hands and fingers. These kinematic modelling resorts to various techniques such as keyframing (Adamo-Villani 2008), optical motion capture (Kitagawa and Windsor 2012, Wheatland et al. 2013) and data-driven methods (Bruderlin and Williams 1995, Majkowska et al. 2006) and can be used in the prediction and synthesis of hand/finger motions.

On the other hand, in order to calculate the dynamic parameters of the local tissues during the motion, efforts have been made in improving the mechanical models for human hands and fingers. Combined with a force or vibration as the stimuli, some theoretical models have been conducted to reveal the possible pathological causes of the symptoms induced by the motivation, especially in the aspects of the change in the pulsatile flow in an artery such as the elastic tube theory (He et al. 2008) and spatial resonance theory (Pattnaik et al. 2012). While most other studies to date have adopted multi-degree-of-freedom (DOFs) linear/nonlinear mechanical-equivalent modelling to evaluate the biodynamic response to the stimuli. This kind of lumped parameter model is suitable for both local areas like fingers and the entire hand-arm systems (Dong et al. 2007).

Also, mechanical analogue is good for overcoming the inter-subject variability, allowing for focusing on both the effects of the given factors, for example, the vibration tools (Marcotte et al. 2010), and whether the newly proposed model is superior to the models adopted before (Dong et al. 2013).

Optimised parameters derived by models are related to the mathematical description of the hand-arm system. It is suggested that the impedance function reflects the driving-point dynamic response coupled with the entire system (Książek 1997) but the transmissibility function is only focused on energy transmitted to local segments (Gurram et al. 1994).

2.5.2 Dynamic biomechanical model (mechanical torsional system)

Based on these simplified models, the rotational torque, flexion-extension effect and other compound constraints could be taken into account to refine the model when considering the joints rotation (Fok and Chou 2010) and tendon force (S Adewusi et al. 2012).

2.5.3 Animal modelling

Apart from the models mentioned above, people are also interested in in-vivo characteristics and anthropometry. As a result, animal models have been presented and tested over the years with the help of anatomical data extracted from animal experiments. For instance, the musculoskeletal monkey model published by Sherwin is able to separate out the dynamic response of interest and is beneficial to the research on neurorehabilitation equipment (Chan and Moran 2006). Studies performed invasively on rat-tail correlate the morphology and immunohistochemistry to a computational model, which can also be treated as an effective aid to study the effects of vibration on the vascular and sensorineural system (Krajnak et al. 2013, Krajnak et al. 2018).

2.5.4 Finite element (FE) model

The finite element (FE) models proposed within the last years yield good graphical simulations and numerical applications containing anatomical structures without directly slicing biological tissue. Due to the complexity of the 3D modelling and the requirement of a lot of computing memory, most present models concentrate on 2D simulation for the 2D section of a part of the hand-arm system (Surajudeen Adewusi et al. 2012) or 3D simulation for fingertip area only (Wu et al. 2006). Compared with mechanical models, FE models are able to analyse more responses such as time-dependent displacement, velocity, vibration power absorption density and stress/strain distributions, serving as useful tools for studying static and dynamic loading conditions. In the 2010s, John Z even made a progress in building a hybrid model that combines the mechanical model with the FE model (Wu et al. 2010).

2.5.5 Empirical model and summary

At present, most of the HAV related modelling adopts biodynamic models based on mechanical analogue, in which the local segment of the human body is regarded as a lumped parameter system with multiple degrees of freedom. This kind of model focuses on two biodynamic responses: mechanical impedance, which is a measure of how apt a system is to follow an applied vibration, and transmissibility, which refers to how much vibration is transferred into the hand-arm system. But the mechanical equivalent model is relatively simple with mainly the skeletal system (sometimes part of the muscular system) involved.

In vivo studies, such as animal models, anatomical substructures are considered and the physiological changes in the body exposed to vibration can be observed directly and effectively. But the physiological differences between humans and animals and the ethical issues such as lessening the value of life, makes them not broadly applicable.

The FE model allows for more complex real-life simulations with dynamic load conditions. More and more studies are needed to make sense of its simulation results in HAV. None of the models proposed so far can integrate vascular, nerve and musculoskeletal systems well.

This study is to analyse the experimental results of HAV using an empirical model. It is considered here mainly because the importance of hand force as a risk factor is not clearly addressed in other models. An empirical model can take into account different factors such as vibration level and force level. And it is developed from actual observations, making it more suitable for assessing and managing HAV exposure in real-world settings. Furthermore, empirical models may be updated and refined over time based on new HAV research, assuring their applicability and alignment with vibration industry standards. However, empirical models are not without limitations. They may suffer from poor experimental design or oversimplified causal relationships between HAV and its physiological effects. Therefore, empirical models are not employed as definitive predictors of certain outcomes, but rather as tools to enhance decision-making.

Chapter 3 Apparatus and methodology

Chapter 3 describes the instruments used in the four experiments of this thesis, of which two are on the vascular response and the other two are on the neural response to the HAV exposure. An introduction to the setup of the equipment, the measurement methods of the acute responses and the data analysis methods for the laboratory studies are given here.

3.1 Introduction of the experimental setup

The experimental setup is composed of two parts: the input system and the output system. Taking the test on vascular response during the exposure as an example, Figure **3-1** here shows the layout of the setting. The left side in the red frame shows the vibration excitation system (input system), and on the right side in the purple frame is what we collect in the test (output system). Like the diagnosis of HAVS, the output of the acute response is mostly based on objective methods for the detection of vascular and neural changes.

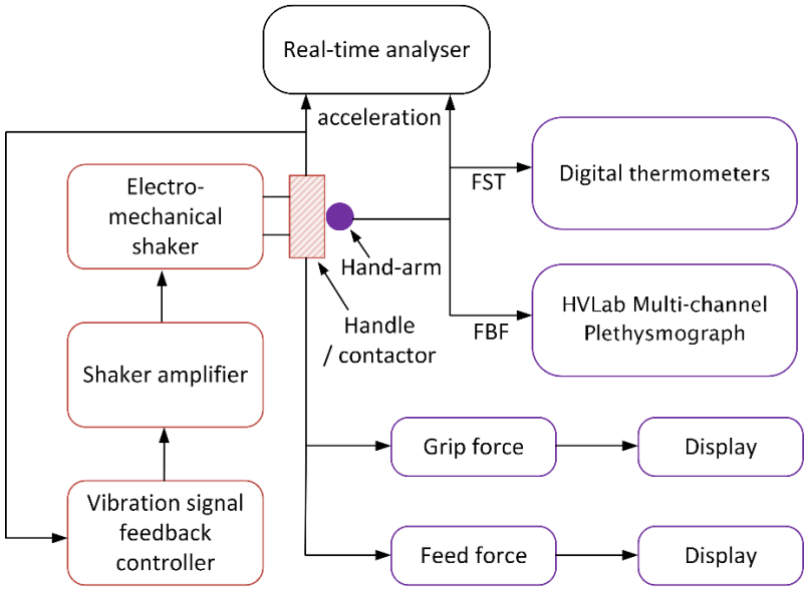


Figure 3-1 Schematic diagram of the experiment set-up for the measurement of vascular response to force-and-HAV exposure.

For vascular measurement, the input and output systems are parallel and can be performed without affecting each other. That is to say, the vascular responses (FBF, FST) can be detected while the subject is exposed to the force and vibration. The flow diagram for measurements of the nervous system is shown in Figure **3-2**. The difference is that the neural responses (VPT, TPT) are measured before and after the exposure.

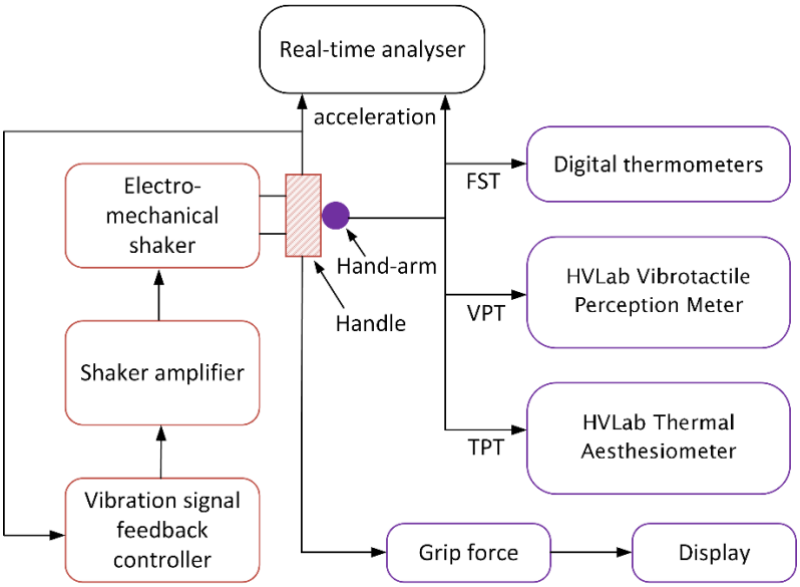


Figure 3-2 Schematic diagram of the experiment set-up for the measurement of neural response to force-and-HAV exposure.

3.2 Instrument and approaches taken

Vibration test facilities are based on the human factors research unit. Pre-calibration is done before the commencement of each trial to ensure that those pieces of equipment utilised are within calibration.

3.2.1 Vibration generator

All the experiments are conducted using an electrodynamic vibrator (or shaker), Derritron VP30, as shown in Figure **3-3**. The produced vibrations are sinusoidal acceleration stimuli with a single frequency of 125 Hz since the Pansini channel found to be associated with vibration disorders is sensitive to vibration stimulation around this frequency. The vibrator is powered by a 300 W amplifier (Gearing and Watson SS_600).

The vibrator produced vibration along the vertical axis and is positioned either vertically or horizontally.

In the case of a vertical vibrator, the vibration is transmitted through a plate (contactor) to the hand pressed on top of it. A tri-axial accelerometer (Brüel and Kjær piezoelectric type) is placed on the base of the plate measuring the magnitude of the vibrational excitation. Whilst the other two tri-axial accelerometers (Kionix KXD94) are attached at the subject's right wrist and right elbow separately measuring the transmitted vibration. The signals from the three accelerometers are amplified by charge amplifiers (Fylde and 128CA) and low-pass filtered (< 200 Hz) and sampled at 512 samples per second by a computer-based analysis system comprising a National Instrument NI

USB-6211 16-bit data acquisition board. The plate comprises a load cell (Tedea Huntleigh 1022) for measurement of the downforce. The measured force is displayed on a force meter in front of the participants to help them keep the hand force at the desired values (deviation less than 4 N).

When the vibrator lies horizontally, an instrumented cylindrical vibrating handle of 40 mm diameter is fixed to the vibrator. As subjects grasp and push the handle using their right hands with the bending-arm position, the vibration is applied to the right upper arms in the z_h-axis direction. A same tri-axial accelerometer (Brüel and Kjær piezoelectric type) is placed on the base of the handle measuring the magnitude of the vibrational excitation. The handle comprises four Kistler force sensors, two for measurement of the grip force and two for the feed and total dynamic force. The measured grip and feed forces are displayed on a screen in front of the participants to help them keep the hand forces at the desired levels (deviation less than 4 N).

Derritron VP30

Outline specification:

Displacement: ±5.7 mm

Acceleration: ~400 ms-2 peak

Frequency range: ~1.0 to 4500 Hz

Table diameter: 146 mm

Maximum unsupported load: 23 kg

Figure 3-3 Vibrator being used to provide translational oscillation.

3.2.2 Transducers

3.2.2.1 Accelerometer sensors

As mentioned above, two types of accelerometers are utilised in the experiment, as the new standard for the evaluation of vibration levels was based on acceleration (unit: m/s²). The first type (Brüel and Kjær piezoelectric type, Brüel & Kjær, Nærum, Danmark) is affixed to the excitation system, typically positioned at the base of the vibration handle or beside the flat contact plate. It is used to monitor and gauge the intensity of the vibration source. The second type is attached to the subject's hand, designed to capture the signals at the receiving end. This device, which we refer to as a MEMS accelerometer (Kionix KXD94, Kionix, Ithaca, NY, USA; sensitivity: 200 mV/g, measuring range: ±10g), detects the residual vibration level transmitted to the forearm. Despite being a three-axis accelerometer, only accelerations in the direction of stimulation are recorded. Both types of accelerometers are shown here in Figure **3-4**.

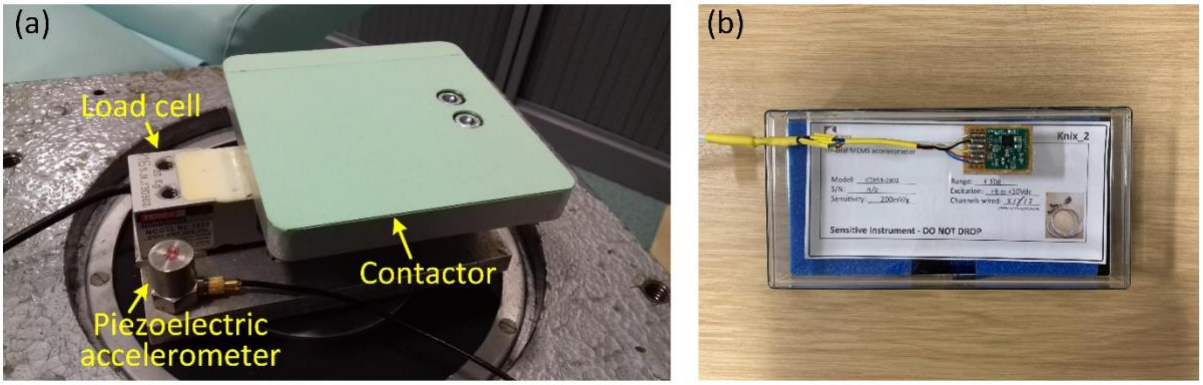


Figure 3-4 Accelerometer sensors being used to measure the vibration. (a) Brüel and Kjær piezoelectric accelerometer for detecting excitation vibration signals. (b) MEMS accelerometer for picking up the vibration transmitted to the forearm.

To ensure accurate measurements, both sensors go through calibration before each test (Figure **3-5**). The Brüel and Kjær one on the excitation side is calibrated using a Brüel and Kjær 4294 calibrator, and the Kionix one on the receiving side using a Rion VE-10 calibrator. Both calibration exciters generate vibrations with a consistent magnitude of 10 m/s² r.m.s. at 159.2 Hz, but their top structures differ, making them suitable for fixing different accelerometers. When the accelerometer is fixed on the calibration exciter, the indicated acceleration falls within the range of 9.8 to 10.2 m/s².

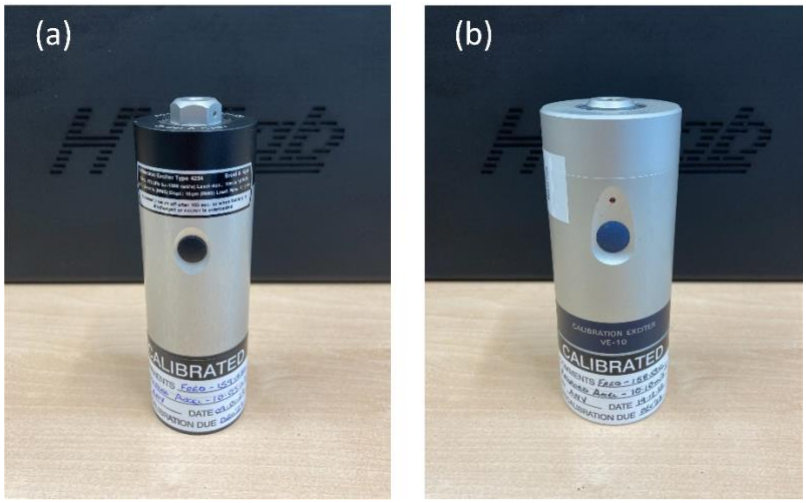


Figure 3-5 Calibration exciters being used to calibrate the accelerometers. (a) Brüel and Kjær calibrator applied for Brüel and Kjær piezoelectric accelerometer. (b) Rion VE-10 calibrator applied for MEMS accelerometer.

3.2.2.2 Force transducer

Depending on the way the hand force is applied to the shaker, two types of force transducers are utilised in the experiment. To continuously monitor the downward contact force exerted on the top of the contactor, a load cell (Tedea Huntleigh 1022) is mounted on the underside of the wooden contactor. This configuration is also illustrated in Figure **3-4**. To track both the grip and feed forces exerted on the shaker handle during exposure to HAV, two built-in force sensors (Kistler; gauge resistance: 120 Ω) are employed.

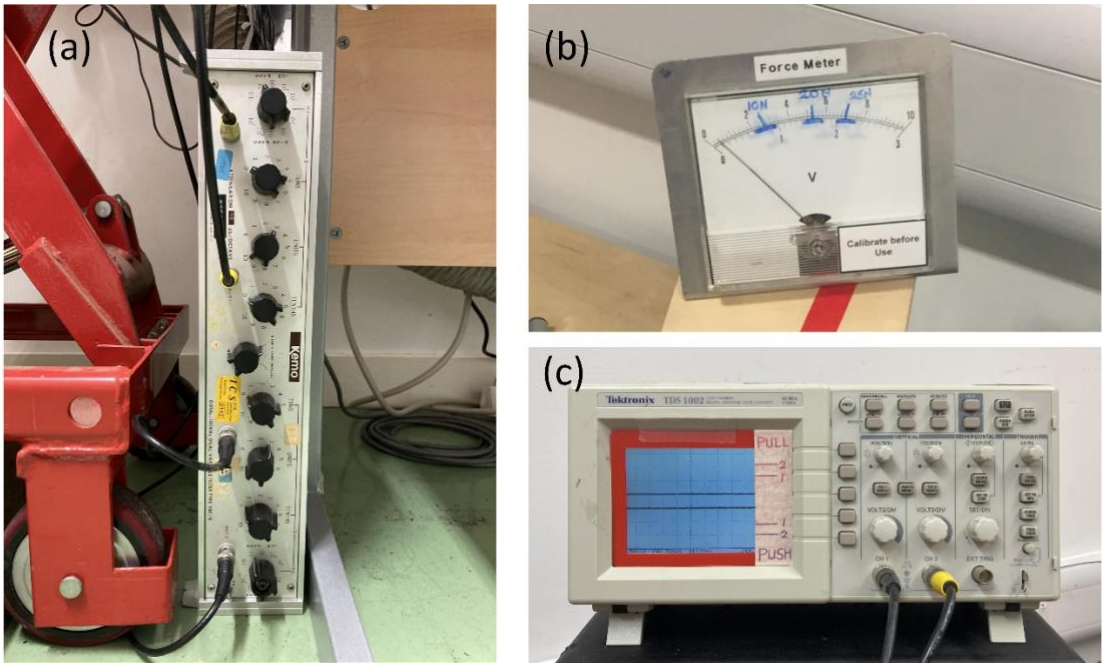


Figure 3-6 (a) Filter being used for force transducers. (b) A force meter able to display a single force. (c) An oscilloscope screen able to display two force channels.

The force signals indicating the applied forces are transmitted to a force meter via an amplifier and a filter. This setup allows the subjects to monitor their exerted forces throughout the testing procedure. The filter goes with the force sensors, as depicted in Figure **3-6**(a), effectively minimises fluctuations caused by high-frequency excitation, ensuring that the measured forces remain stable (cut-off frequency at 3 Hz).

The force measured from the load cell is displayed on the force meter, as shown in Figure **3-6**(b). While the forces measured by the handle force sensors, including both grip and feed forces, are presented on an oscilloscope screen, given that two channels are dedicated to these measurements (Figure **3-6**(c)).

3.2.3 Vascular response measurement

Detection of finger peripheral circulation is based on two acute measurements: the finger blood flow (FBF) test and the finger skin temperature (FST) test. FBF test is estimating the rate at which blood enters the finger. FST test is monitoring the change in the temperature of the finger skin during and after the HAV, rather than after an extra cold provocation as in a FST rewarming test. These two methods have been used as useful indicators of acute vascular response to HAV and tend to be correlated.

3.2.3.1 FBF test

Test of finger blood flow (FBF) is presented on the subjects by strain-gauge venous occlusion plethysmography. This technique has been refined over time, since initially introduced by Hewlett & van Zwaluwenburg a century ago. In this thesis, the measurement of arterial blood flow to the fingers is following the method proposed by Greenfield et al (Greenfield et al. 1963).

Figure 3-7 Strain-gauge plethysmography being used for test on finger blood flow.

The devices and the process for monitoring digit circulation are non-invasive. Pressure cuffs (Hokanson) for air inflation are attached around the subject's middle phalanx and were airtight to prevent pressure loss; while mercury-in-silastic (now Galinstan) strain gauges are applied at the nail base to monitor rises in resistance and fingertip volumes during venous occlusion, so that the change in FBF could be derived. Although the strain gauge is slightly extended, it is not too tight to impede blood flow. Both the pressure cuff and strain gauge are connected to an HVLab Multi-channel plethysmograph (CE marked medical device, University of Southampton), as shown in Figure 3-7.

The FBF measurement involves three components: the calibration pulse, the application of venous occlusion, and the measurement of finger volume using the strain gauge. The baseline strain gauge resistance is established during the

calibration pulse. Venous occlusion is then applied by inflating the cuff to the desired pressure (around 60 mmHg), temporarily stopping venous blood flow while maintaining arterial inflow.

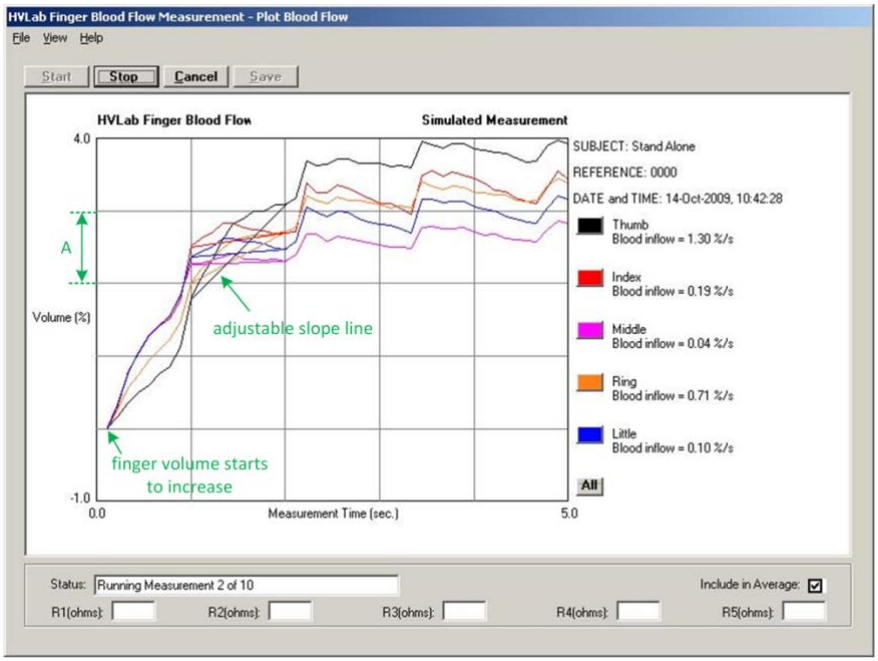


Figure 3-8 Results of finger blood flow measurement. A (mm) is the height of a calibration pulse corresponding to a 1% increase in finger volume. Changes in finger volume are determined by fitting a tangent (adjustable slope line) to the blood flow curves following venous occlusion.

The results of the FBF test are displayed in real-time once the occlusion starts. As seen in Figure **3-8**, the plethysmograph gives out a chart showing the increase in finger volume over time, which corresponds to the rise in the resistance of the strain gauge (Lewis 1996, Welsh and Griffin 2004). The assumption is made that the digit was cylindrical and that volume changes occurred in the transverse direction. The blood influx, Ain, in ml of blood per 100 ml of tissue per second (equal to the percentage increase in finger volume per second), is calculated from the gradient of the trace following venous occlusion.

To determine changes in finger volume, a tangent line is fitted to the FBF curves that appear after venous occlusion. The initial part of the blood flow curve, which may contain artefacts, is disregarded. The tangent is formed by connecting either the systolic peaks or the diastolic troughs of the FBF curve over the steepest period between one and two seconds after the occlusion pressure is applied. Measurements of blood flow could be measured at up to five locations simultaneously.

3.2.3.2 FST test

FST test is more straightforward and conducted by digital thermometers. The thermocouple probe is attached to the fleshy upper part of a finger, taking the temperature and giving out a numerical reading on an LCD screen (Figure 3-9). Each thermometer has two channels, able to give results at two measuring ends at the same time. The temperature shown is in degrees (°C). This non-invasive method provides a decimal point accuracy but is easily affected by the surrounding room temperature.

Figure 3-9 Digital thermometer being used for test on finger skin temperature.

3.2.3.3 Pre-test on FBF and FST

It is important to acknowledge procedural artefacts that may potentially impact the accuracy of FBF and FST measurements. Before our formal investigations, several small tests were carried out to examine the impacts of various factors in venous occlusion and temperature measuring methods.

The findings suggested that there was no discernible difference between occluding one single finger and multiple fingers of the same hand in terms of FBF. Also, whether the left hand was experiencing measurement or not did not affect the FBF results of the right hand. This indicated that the occlusion of each finger was independent, and multi-channel measurement was as reliable and consistent as single-channel measurement. Additionally, the placement of the cuff in the middle and proximal parts of the finger segment did not have a significant effect on the FBF results.

It was noted that changes in FST exhibited a certain delay relative to changes in blood flow. Therefore, a longer duration should be allocated for recording the temperature changes. When gripping the handle, the FST at the contact surface would vary (usually decrease) as the handle was made of metal with a low specific heat capacity. Thus, the thermocouple probe was then attached to the dorsal surface of the fingertip rather than the ventral side to minimise the potential influence of the handle material on the measured temperature. Furthermore, the reading of FST was unaffected by the number of measurement channels.

3.2.4 Neural response measurement

Detection of hand nerve function is based on two acute quantitative sensory testing (QST): the vibrotactile perception threshold (VPT) test and the thermotactile perception threshold (TPT) test. VPT test is intended to measure the vibration magnitude at which a vibration stimulus can be just perceived at the fingertips. TPT test is measuring the tactile perception thresholds for thermal stimuli (i.e. the minimum change in temperature that can be perceived) at the fingertips. Both of them are non-invasive and commonly used and standardised for the diagnosing of sensory changes associated with chronic peripheral neuropathy (Lindsell and Griffin 1998, ISO 2001b), as well as for the detection of acute sensorineural responses to HAV: the temporary threshold shifts (TTS) of vibratory sensation and thermal sensation.

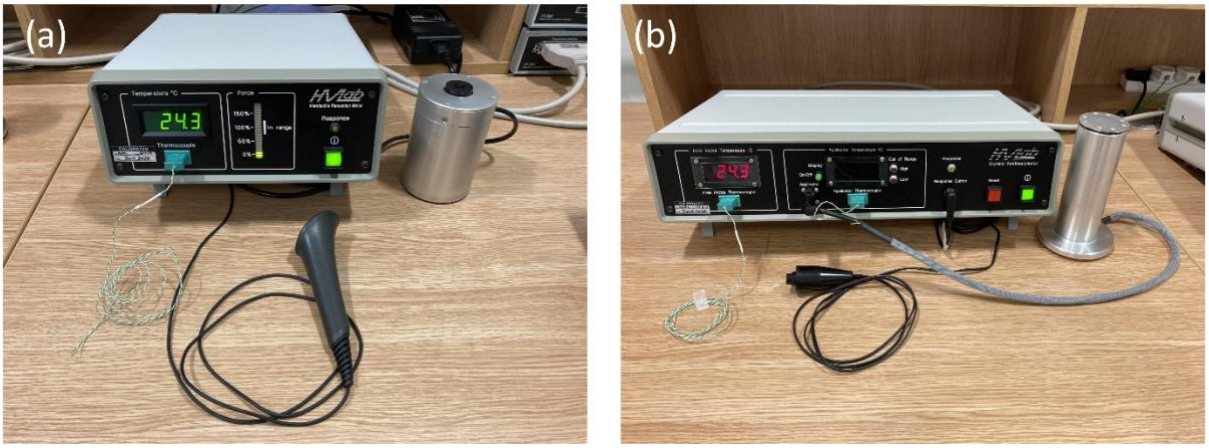


Figure 3-10 Devices being used for detection *of* neural response to hand-arm vibration. (a) HVLab Vibrotactile Perception Meter (VPM) for test on vibrotactile perception threshold. (b) HVLab Thermal Aesthesiometer for test on thermotactile perception threshold.

3.2.4.1 VPT test

VPT test is executed by the *HVLab* Vibrotactile Perception Meter (VPM), controlled by the *HVLab* Diagnostic Instruments Manager software, running on a personal computer (Figure **3-10**(a)). The VPM system is made of vibratory modules and response modules. The vibratory modules come supplied with a vibrating probe (a diameter of 6 mm) and a surround (a diameter of 10 mm) at the top of the applicator. A vibration signal at 31.5 Hz or 125 Hz is sent to the probe on which the subject's finger presses downward to maintain good contact. The force exerted on the surround is measured using strain gauges and feedback is provided by a force meter on the front of the control box. A response button is held on the contralateral hand and going to be depressed as soon as vibration is felt by the ipsilateral exposed finger.

During the VPT test, subjects are supposed to undergo the following steps:

(a) Place one finger onto the top of the probe, allowing the centre of the whorl on the fingertip to be situated over the centre of the probe.

(b) Monitor the force feedback on the control box and press down gently on the probe until the meter reads 100 %. Keep the pressure on the probe so that this remains at 100% throughout the test.

(c) Hold the response button unit in the contralateral hand with the thumb over the button.

(d) When a vibration can be felt at the probe, press the response button and keep it pressed until the vibration can no longer be felt. When there is no vibration sensation, release the button until the vibration is felt again (i.e. when you can feel the vibration, the button should be down, when you can't feel the vibration, the button should be up).

(e) Repeat step(d) until the experimenter informs that the test is complete.

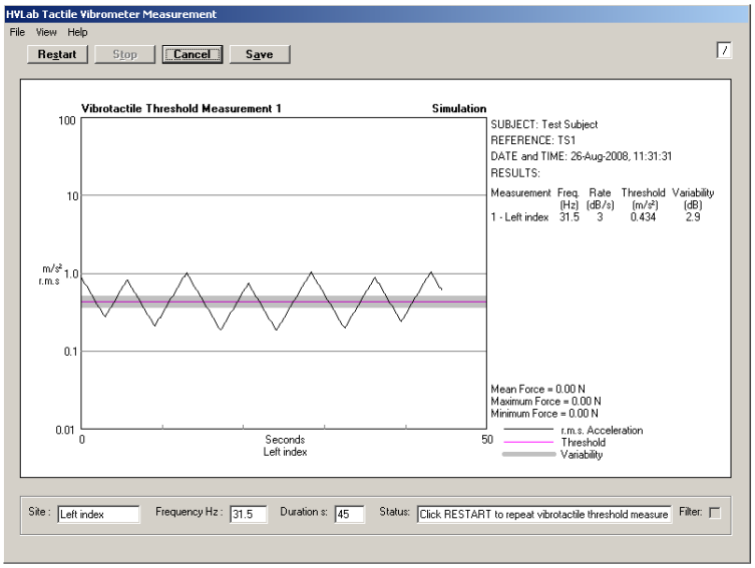


Figure 3-11 Results of vibrotactile threshold measurement.

The vibrogram is displayed in real-time as the response button in pressed and released. Once the measurement is complete, the mean threshold and the variability are displayed in acceleration units (i.e. ms^{-2} r.m.s.) in the vibrogram (Figure **3-11**). The thin pink line in the vibrogram represents the threshold and the grey band represents the variability of the reversals. The threshold is calculated using the geometric mean of the reversals. The variability displayed is either the difference between the highest peak and the lowest peak or the difference between the highest trough and the lowest trough, whichever value is higher. The results can be processed in dB as well relative to 10^{-6} ms^{-2}. The conversion between acceleration and decibel follows the equation: $T = 20 \log_{10} t + 120$, or $T = 20 \log_{10} (t/t_{ref})$ (where T is the vibrotactile threshold in decibels, t is the vibrotactile threshold in ms^{-2} and the reference value t_{ref} is 10^{-6} ms^{-2} (Lundström et al. 1999, Sakakibara et al. 1996).

3.2.4.2 TPT test

TPT test is executed by the *HVLab* Thermal Aesthesiometer (TA), controlled by the *HVLab* Diagnostic Instruments Manager software, running on a personal computer (Figure **3-10**(b)). The TA system is also made of vibratory modules and response modules. The vibratory modules come supplied with an applicator that incorporated a Peltier semi-conductor heat pump through which the temperature is provided. The pump is covered by a thin metal contact plate at the top, allowing the subject's finger to rest on that. The reference temperature for both warm threshold (TPTw) and cold threshold (TPTc) tests is set at 32.5°C. A response button is held on the contralateral hand and going to be depressed as soon as a temperature change (either increase or decrease) is felt by the ipsilateral exposed finger.

During the TPT test, subjects are supposed to undergo the following steps:

(a) Rest the finger on the top of the applicator so that the fleshiest part of your fingertip is in the centre of the contact plate.

(b) Make sure that during the test procedure, you maintain contact with the applicator contact pad without exerting excessive pressure.

(c) Hold the response button in the opposite hand with the thumb over the button.

(d) When a change in temperature of the contact pad was perceived, press the response button and then release it; the temperature would return to its original level.

(e) repeat step(d) until the experimenter tells you the test is complete.

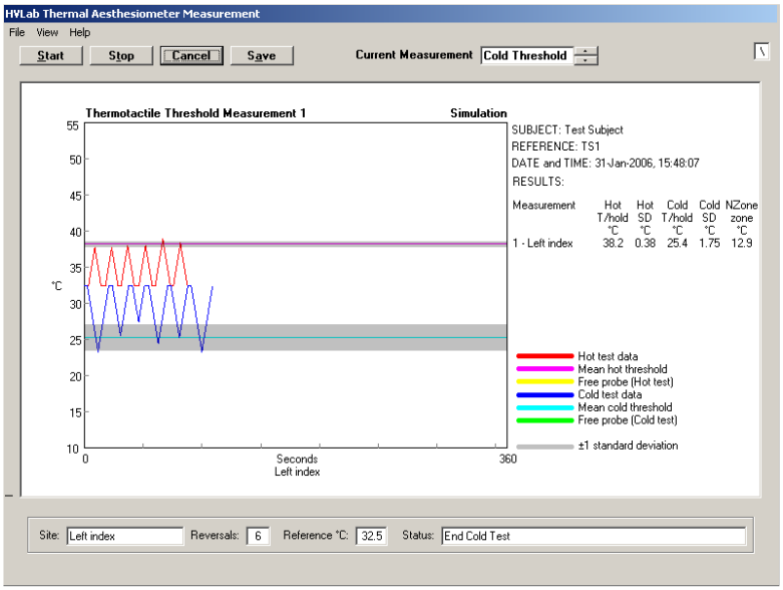


Figure 3-12 Results of a Hot and Cold Thermotactile Threshold Measurement.

The thermogram is displayed in real-time as the response button in pressed and released. Once the measurement is complete, the warm and cold mean thresholds and the standard deviation are

automatically calculated and displayed in degrees Celsius (i.e. °C). As seen in Figure **3-12**, the thin pink line in the thermogram represents the threshold and the grey band represents the variability of the reversals. The threshold is calculated using the geometric mean of the peaks and troughs. The variability displayed is either the difference between the highest peak and the lowest peak or the difference between the highest trough and the lowest trough.

3.2.5 Other measurement

Room temperature and humidity. A thermos-hygrometer with a digital screen is used to measure the temperature and humidity in the room (Figure **3-13**(a)). At the same time, the room temperature is displayed on the VPM and TA and manually recorded.

Hearing protector. The vibrator generates noise when working, with the air cooler of the vibrator being the primary source of noise in the laboratory, as it remains constantly active. To minimise the impact of background noise, particularly for the measurement of the finger sensory threshold, participants are required to wear passive noise-cancelling headphones (Figure **3-13**(b)) throughout the test.

Anthropometric data. Subjects' hand sizes are measured following the guidelines of BS EN ISO 21420:2020 (ISO 2020). Hand circumference is measured with tape, 2cm from the crotch between the thumb and the index finger. Hand length refers to the distance between the wrist and the tip of the middle finger.

Grip strength. The assessment of grip strength involves the use of a dynamometer (Figure **3-13**(c))—a device held by the subject in the palm, which is squeezed with maximum force using the fingers.

Figure 3-13 (a) A thermos-hygrometer to digitally display the room temperature and humidity. (b) Hearing protectors being worn by subjects during the test. (c) Hand dynamometer for measurement of hand grip strength.

3.3 Statistical methods

The sample size plays a crucial role in determining the likelihood of detecting an effect in a significance test. In our study, the calculation of the sample size was based on the statistical Power Analysis. Prior to the formal test, a pre-test would be conducted to gather the necessary inputs for the power analysis, such as the data variability. The minimum detectable difference was defined in alignment with the desired level of statistical power (0.8), significance level (0.05) and effect size (0.2).

The statistical analysis of the collected data is performed using SPSS Statistics 27. Both parametric and non-parametric statistical methods are given here in Table **3-1**, with a preference for non-parametric tests in this study due to the non-normal distribution of the measured data.

Table 3-1 Summary of parametric and nonparametric statistical methods according to different cases.

case	**Parametric statistical tests**	**Nonparametric statistical tests**
Two independent groups	Independent t-test	Mann-Whitney U test
two related groups	Paired t-test	Wilcoxon signed-rank test

K related groups	Repeated Measures ANOVA	Friedman two-way analysis of variance
Correlation between two variables	Pearson product-moment correlation coefficient	Spearman rank-order correlation coefficient

Chapter 4 Experiment 1: Acute vascular response to force and vibration

4.1 Experiment background

Many factors are found to contribute to increasing the risk of HAV-related vascular disorders, and grip and push forces (also known as feed forces) are believed to be two of the most influential variables. However, research has not been done on the relationship between acute changes in blood circulation and these active forces under exposure to the hand-arm vibration, especially with regard to the alteration in finger blood flow in the handgrip position.

In fact, it is unlikely to separate the received vibration from the force exerted on the vibrators. The human body responds to the combined effect of force and vibration, rather than to the vibration alone, and the real impact on human hands can be reflected in time by the change in blood circulation. As a result, the question to be answered by this experiment is: does hand-arm vibration result in different levels of finger vasoconstriction depending on different combinations of grip and push exertions? This study was to investigate the acute change in finger blood flow and finger skin temperature during and after exposure to hand-arm vibration combined with different grip and push exertions and to find out which active force situation will have the most effect on blood vessels.

4.2 Experiment hypotheses

- When the magnitude of vibration is constant, the degree of finger vasoconstriction (decrease in finger blood flow and finger skin temperature) would depend on the exerted force.

- Grip force would play a more important part in circulatory disturbances than feed force.

4.3 Participants

Vibration-induced disorders suffered by affected patients are reported to be chronic cases. While in the laboratory, we tended to study the acute effects of HAV in healthy people without vibration history, which appears to be important indicators of long-term effects and assist in early detection.

Up to 12 male subjects participated in the experiment. All of them were students from the University of Southampton. They were recruited by word of mouth or email. Prior to the test, subjects had 24 hours after receiving participant information sheets to decide whether they were

interested in participating or not. A consent form and health questionnaire were completed by each subject willing to take part in the study.

The mean stature and mean mass of the subjects were 174.2 (SD 5.3; range 165-183) cm and 71.5 (SD 9.2; range 55-83) kg. Hand sizes were measured according to BS EN ISO 21420:2020 (ISO 2020). Their mean hand circumference was 19.3 (SD 1.1; range 17-21.5) cm, and their mean hand length (distance between the wrist and the tip of the middle finger) was 18.4 (SD 0.8; range 17.0-20.0) cm.

4.4 Apparatus and approaches taken

The experiment was conducted using an electrodynamic vibrator, Derritron VP30, powered by a 300 W amplifier. The shaker produced vibration along the vertical axis and was positioned horizontally as displayed in Figure **4-1**. An instrumented cylindrical vibrating handle of 40 mm diameter was fixed to the shaker. The handle comprised four Kistler force sensors, two for measuring the grip force and two for the feed and total dynamic force. The measured grip and feed forces were low-pass filtered and displayed on a screen in front of the participants to help them keep the hand forces within the desired ranges.

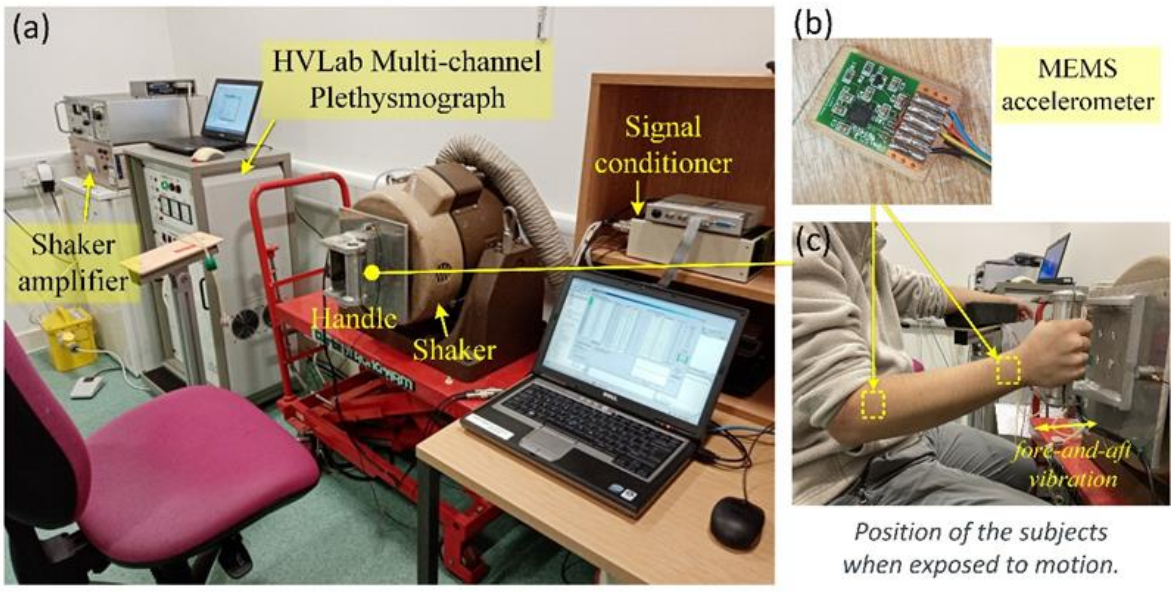


Figure 4-1 (a) The experimental set-up. (b) The tri-axial accelerometers used to measure the vibration transmitted to the subject. (c) The close-up shows the posture and position of the subject when exposed to the motion by grasping the instrumented handle. Two accelerometers were attached to the subject's wrist and elbow respectively fastened by micropore tape.

There was a tri-axial accelerometer (Brüel and Kjær piezoelectric type) placed on the base of the handle measuring the magnitude of the vibrational excitation. Whilst the other two tri-axial accelerometers (Kionix KXD94) were attached to the subject's right wrist and right elbow separately

measuring the transmitted vibration. The accelerometers weighed around 5g, which were light enough that they would not affect the movement of the arm.

Test of finger blood flow (FBF) was presented on the subjects by strain-gauge plethysmography. Pressure cuffs (Hokanson) for air inflation were attached around the subject's middle phalanx and strain-gauge was applied at the nail base to monitor rises in fingertip volumes during venous occlusion, so that the change in FBF could be derived. Both the pressure cuff and strain gauge were connected to an HVLab Multi-channel plethysmograph (CE-marked medical device, University of Southampton). This method is a non-invasive method to monitor the digit circulation which has been described in the literature (Greenfield et al. 1963, Welsh and Griffin 2004).

Test of finger skin temperature (FST) was resorting to a digital thermometer fastened by micropore tape to the middle phalanx of fingers on the backside. A mercury thermometer displayed the room temperature on its screen with an accuracy of ±0.5°C.

4.5 Motion stimuli and force range

In this study, subjects were required to grasp and push an instrumented vibrating handle using their right hands with the bending-arm position, as shown in Figure **4-1**(b). The vibration signals were generated by MATLAB and the HVLab toolbox, transmitted through the handle and applied to the right hand in Z_h-axis direction. The produced vibrations were sinusoidal acceleration stimuli with a single frequency of 125 Hz as the Pansini channel found to be associated with vibration disorders was sensitive to vibration stimulation around this frequency. The vibration magnitude was set as weighted 2.75 m/s^2 r.m.s. (unweighted 22 m/s^2 r.m.s.) and the total amount was 0.6522 m/s^2 r.m.s. in A(8) value. Subjects were supposed to attend one session with different force and vibration conditions, each of which involved holding the handle for three minutes. It was designed to reduce the length of time exposed to the stimuli in one go, by having a break of four minutes or more in between. The excitation levels of vibration, both the magnitude and duration, were controlled under the daily exposure limit set by the Health and Safety Executive (HSE).

As the hypothesis suggests, there should be a significant difference between conditions with different hand forces attached to the handle. It was therefore necessary to select the grip and push/feed strength with an obvious difference but within a reasonable range. Both of the magnitudes of grip and feed forces were adjusted to 10 N and 50 N (less than 65% of maximal grip strength), to produce enough range effect as well as limiting the overall discomfort.

To compare the effects of hand forces alone and the combined effects of hand force and vibration, situations broke down into two groups: the vibration group and the control group. The vibration group combined HAV and forces stimuli, and the control group only had a force applied. Based on

the cross-combination of grip and feed forces, there were four situations in each group as shown in Table **4-1**.

Table 4-1 The eight force-and-vibration situations experienced by subjects.

Vibration group	G10 + F10 + HAV (V11)	G50 + F50 + HAV (V55)	G10 + F50 + HAV (V15)	G50 + F10 + HAV (V51)
Control group	G10 + F10 (C11)	G50 + F50 (C55)	G10 + F50 (C15)	G50 + F10 (C51)

G: Grip force (N); F: Feed force (N).

4.6 Procedure

Each subject attended one session lasting around 1.5 hours. Prior to the test, subjects avoided alcohol and tobacco for 12 hours and caffeine assumption for 2 hours to minimise the influence of alcohol, tobacco, and caffeine on their blood circulation. Subjects were habituated at room temperature for five minutes before the tests begin. The maximal grip strength of each subject was measured.

During the session, participants were asked to take a relaxed upright seating position with their left arms and hands supported at the heart level. Their right hands hold an instrumented handle with a bending-arm posture at a similar height (slightly lower), under eight force-and vibration conditions as described. In each condition, subjects experienced a period of seven minutes:

- Period 1: no force and no vibration (2 min): measurement of FBF, FST
- Period 2: force (and vibration) (3 min): measurement of FBF, FST, accelerations
- Period 3: no force and no vibration (2 min): measurement of FBF, FST

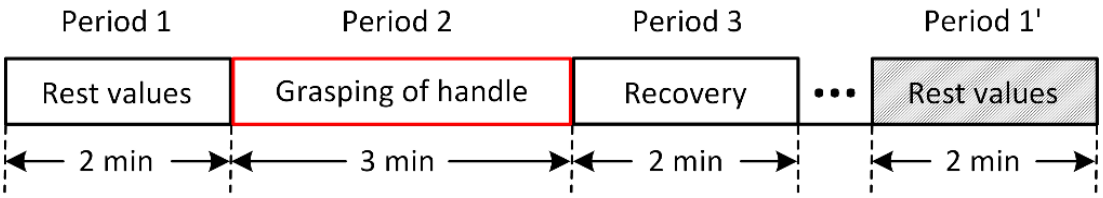


Figure 4-2 Timeline events during one experimental trial. Subjects experience various force-and-vibration conditions during period 2 by grasping the handle. Period 1 of the following trial can be regarded as the latter part of the recovery period of the previous round.

For the vibration group, a 3-min sinusoidal 125-Hz vibration at 22 m/s^2 rms (unweighted) was applied during period 2 followed by a 2-min recovery period. After that, subjects were allowed to have an extra break and adjust the amount of the next attached force, while keeping sitting comfortably at all times. Different conditions were carried out in random order.

Measurement of FBF was taken every 30 s in the right index and fourth fingers, and also in the index, and fourth fingers of contralateral (left) hands. FST was recorded every 30 s in the middle fingers of both hands. Accelerations at the right wrist and right elbow were measured during period 2 to calculate the transmissibility related to the vibration dissipation or absorption.

4.7 Data analysis

FBF and its percentage change (%FBF) were introduced to avoid unintentional changes in flow velocity during different test periods, while the absolute value of FST was used directly as the room temperature was controlled. The vibration transmissibility was determined by the amplitude ratio of the input acceleration at the handle to the transmitted acceleration measured by the accelerometers on the forearms.

The data were analysed using the non-parametric method in SPSS. To quantify the significance of the differences in the FST and %FBF, the Friedman test and the Wilcoxon matched-pairs signed-ranks were performed between conditions with different hand forces and vibrations. Additionally, the Spearman correlation analysis of finger blood flow and transmissibility was carried out to determine the dependence of vasoconstriction in the fingers on the absorbed vibration in the forearm. Statistical significance was indicated when the p-value fell below 0.05.

4.8 Results

While access to facilities and labs is currently possible, finding enough volunteers willing to take part in the test during this special period is still challenging. 12 experimental participants have attended the experiment and analysis has been done based on the collected data.

The 12 subjects were healthy men aged between 22 and 29 years (mean 25.3, SD 2.15). They were screened using a health questionnaire to exclude those with a vibration exposure history or other medical problems known to affect finger circulation. The experiment was conducted in a clinic at a controlled room temperature of 24 ±2°C (mean 25.05, SD 1.20).

Figure **4-3** below presents the overall pattern of the median values of FBF (expressed as % of pre-exposure) in the index and fourth right (exposed, ipsilateral) fingers, and the index and fourth left (unexposed, contralateral) fingers across the 7-min period and the eight exposure conditions.

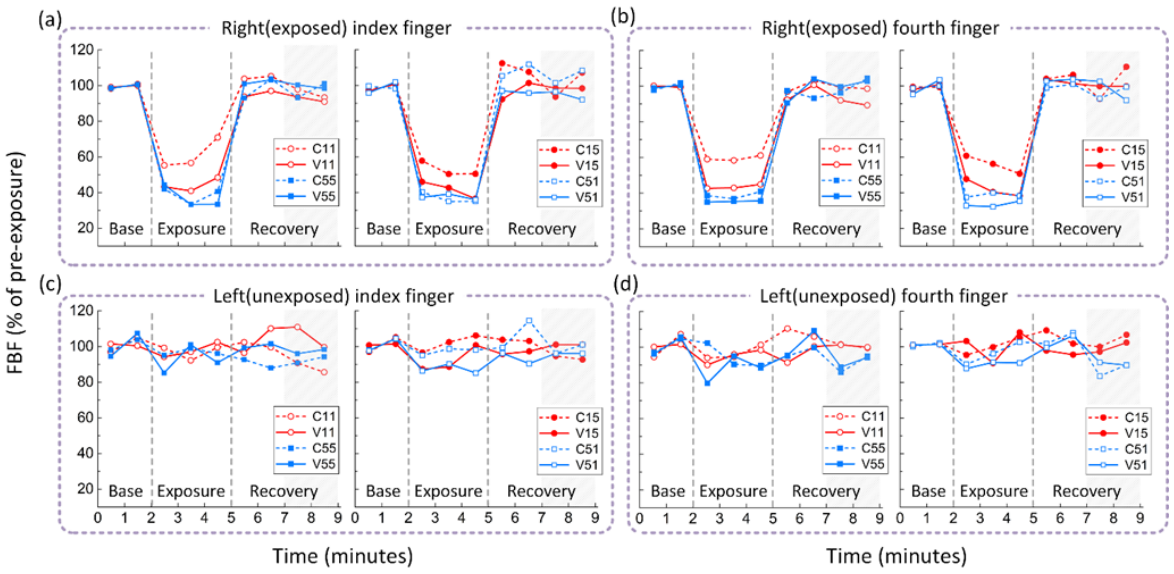


Figure 4-3 Finger blood flow (% of pre-exposure) in the index and fourth right fingers (R2, R4, ipsilateral to hand force and vibration), and the index and fourth left fingers (L2, L4, contralateral) during right exposure conditions (see Table **4-1**). Plotted symbols are median values. Two dash lines correspond to the time points at which exposure begins and ends, respectively.

4.8.1 Finger circulation during the pre-exposure period

Before exposure to either hand force alone or in combination with vibration, no significant changes in FBF were found for both hands across the eight experimental conditions ($p = 0.052–0.369$, Friedman). During period 1, FBF averaged 3.81 ml/100 ml/s in the index right finger, 3.99 ml/100 ml/s in the fourth right finger, 3.67 ml/100 ml/s in the index left finger, and 3.40 ml/100 ml/s in the fourth left finger. The rest levels of exposed fingers were slightly higher than that of unexposed fingers, which may be the result of the right arm bending close to the heart and the left arm straightening naturally.

The baseline measure of FST varied between subjects and is in the range 30.5–34.8°C for both hands. As can be seen in Figure **4-4** below, FST was not exactly the same at the beginning of different conditions, but the sets of measures of FST in each condition did not differ during the pre-exposure period (right hand, $p = 0.716$; left hand, $p = 0.088$; Friedman). There were no significant differences in the pre-exposure measures of FST between the exposed and unexposed fingers ($p = 0.715–1.000$, Wilcoxon).

The initial values of FBF and FST varied among different subjects, but neither FBF nor FST was found to be correlated to the subjects' BMI ($p = 0.193–0.871$, Spearman).

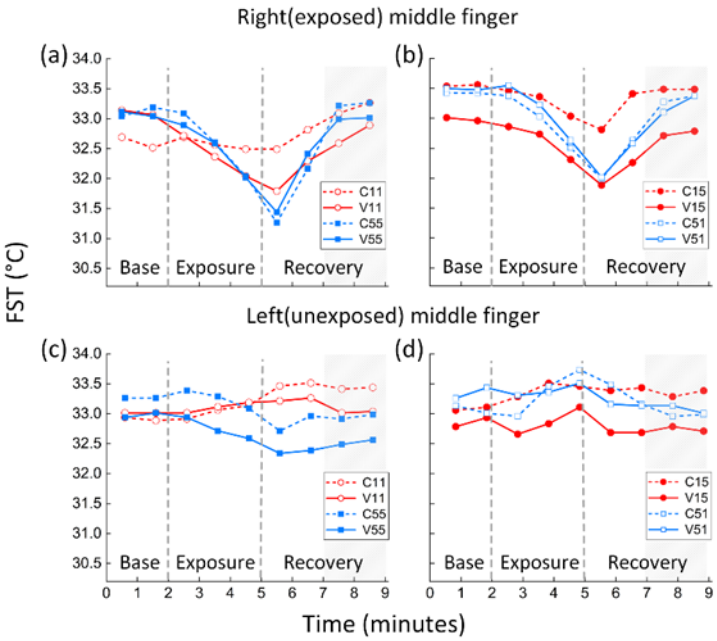


Figure 4-4 Absolute change of finger skin temperature in the left (unexposed) fingers and right (exposed) fingers every minute during the eight exposure conditions (see Table **4-1**). Two dash lines correspond to the time points at which exposure begins and ends, respectively. The resting period of each following round was considered the latter part of the recovery period of the previous round. Plotted symbols are median values of FST.

4.8.2 Effects of hand force on finger circulation

As shown in Figure **4-3**, exposure to hand force alone during period 2 induced a clear fall in FBF in two exposed right fingers compared to the pre-exposure (period 1) and the recovery (period 3) ($p < 0.05$, Wilcoxon).

For any case in the control group, the blood flow in the right finger decreased significantly at the time of force exposure and persisted for the rest of the exposure period ($p < 0.05$, Wilcoxon). When compared with the resting level, a grip force of 10 N and a feed force of 10 N (condition C11) provoked a certain degree of reduction in FBF in right fingers (a drop of 39.61%), while condition C55 (50 N grip force + 50 N feed force) was associated with a greater decrease in FBF (a drop of 62.29%, Table **4-2**) ($p = 0.002$, Wilcoxon). Moreover, exposure to condition C51 (grip force of 50 N combined with 10 N feed force) during period 2 affected FBF to a larger extent than condition C15 (grip force of 10 N, feed force of 50 N) ($p = 0.002$, Wilcoxon). A similar reduction of FBF can be observed between conditions C11 and C15 (both with 10 N grip force), as well as between C55 and C51 (both with 50 N grip force) ($p = 0.153–0.753$, Wilcoxon). After the cessation of force exertion, FBF in the right fingers recovered fast and fluctuated within the normal range ($p = 0.012$, Wilcoxon).

The lowering in FBF in the left (unexposed) finger during period 2 was marginally not significant when compared to that in the right fingers. As shown in Figure **4-3Error! Reference source not found.**, no significant difference in FBF was observed between two left fingers or two right fingers (right hand, p = 0.424; left hand, p = 0.414; Wilcoxon).

Table 4-2 Alterations in finger blood flow.

Percentage change in FBF (% of pre-exposure) for left and right fingers over eight exposure conditions; the alterations in FBF were calculated as the differences between the mean value of median FBF in two fingers of each hand at exposure period 2 and the resting level of FBF during pre-exposure. Values given in parentheses are the range of quartiles (namely, Q1–Q3).

	C11	*V11*	*C55*	*V55*
Left (unexposed) finger	99.94% (88.47%–104.91%)	95.93% (89.61%–102.76%)	90.62% (86.65%–99.30%)	88.61% (74.32%–103.90%)
Right (exposed) finger	59.72%** (47.42%–72.95%)	47.16%** (32.06%–61.41%)	43.72%** (26.46%–51.83%)	41.11%** (30.90%–46.19%)

	C15	*V15*	*C51*	*V51*
Left (unexposed) finger	100.93% (93.09%–112.05%)	92.62% (83.92%–109.33%)	97.86% (77.49%–106.45%)	83.26% (77.70%–99.16%)
Right (exposed) finger	51.96%** (43.48%–75.24%)	45.16%** (37.54%–55.55%)	39.61%** (34.87%–48.80%)	40.38%** (25.87%–61.40%)

*p < 0.05; **p < 0.005.

Slightly different results can be found in the change of FST, as can be seen in Figure **4-4**. Relative to FST without force during period 1, exposure of the right fingers to hand force resulted in a significant reduction in FST of the exposed fingers under conditions C55 and C51 (both with 50 N grip force) (p = 0.005–0.019, Wilcoxon), whereas there were no significant decreases in right fingers' FST when exposed to conditions C11 and C15 (both with 10 N grip force) (p = 0.114–0.182, Wilcoxon). For the unexposed contralateral fingers, none of the conditions induced a pronounced fall in FST (p = 0.060–0.722, Wilcoxon; Figure **4-4** and Table **4-3**). It should be noted that the decline

of FST was more slowly. A gradual reduction of FST was observed in the right fingers from the beginning of period 2 and the downward trend continued even after the exposure. In this experiment, the minimum temperature was reached at approximately the first minute during period 3 of each case. According to the Wilcoxon test, exposure to condition C55 during period 2 provoked a greater reduction at the first minute during recovery in FST than condition C11 ($p=0.003$), while differences were not significant between any other pairs with only one of the forces changed ($p = 0.125–0.969$, Wilcoxon).

Table 4-3 Alterations in finger skin temperature.

Percentage change in FST (% of pre-exposure) for left and right fingers over eight exposure conditions; the alterations in FST were calculated as the differences between the median FST at the first minute during recovery and the resting level of FST during pre-exposure. Values given in parentheses are the range of quartiles (namely, Q1–Q3).

	C11	*V11*	*C55*	*V55*
Left (unexposed) finger	100.64% (100.22%–101.17%)	100.22% (99.61%–101.84%)	99.24% (97.43%–100.74%)	98.36% (97.92%–99.05%)
Right (exposed) finger	98.05% (96.07%–99.37%)	96.57% (93.95%–98.03%)	95.95%* (94.45%–96.07%)	96.20%* (95.15%–97.19%)

	C15	*V15*	*C51*	*V51*
Left (unexposed) finger	100.77% (100.40%–101.69%)	99.74% (98.01%–99.94%)	100.48% (99.40%–101.36%)	99.66% (98.34%–99.95%)
Right (exposed) finger	97.56%** (97.02%–98.46%)	96.54%** (95.89%–97.98%)	96.24%** (95.48%–97.49%)	96.00%** (95.33%–96.42%)

*$p < 0.05$; **$p < 0.005$.

4.8.3 Combined effects of hand force and vibration on finger circulation

Consistent with the findings with the sole force exposure, hand force combined with 125 Hz vibration resulted in reduced FBF and FST in all exposed fingers, compared to the resting period with no force and no vibration ($p = 0.012$, Wilcoxon).

A fall-off response in FBF in the right (exposed) fingers was observed in all the cases exposed to vibration. However, on the basis of the existing force, the overlay influence of vibration on FBF in exposed fingers was not highly significant ($p = 0.189–0.668$, Wilcoxon) except for the pair C51 and V51 ($p = 0.030$, Wilcoxon). Instead, the change of %FBF relative to baseline measures in exposed fingers was similar to each other within the vibration group, as shown in Figure **4-3** ($p = 0.241–0.668$, Wilcoxon). The median blood flow change of the vibration group can be even smaller than that of the control group when increasing the grip force to 50 N.

For left (unexposed) fingers, the vascular results showed that the FBF kept consistent over time with the exception of condition V51 ($p = 0.016$, Wilcoxon). Also, the vibration group did not induce more %FBF reduction compared to the control group in the left hand during period 2 ($p = 0.424–0.587$, Wilcoxon).

Although less pronounced than the %FBF reductions in right fingers, some significant circulatory effects of HAV were observed in the %FST during period 2. Different from the control group, the decreases in %FST relative to baseline measures in fingers exposed to vibration were significant across all the force conditions ($p = 0.002–0.003$, Wilcoxon). An interesting finding was that, within the vibration group, the Wilcoxon test revealed that exposure to condition V55 caused more decrease of FST in exposed fingers than either condition V11 or V15 (both with 10 N grip force) ($p = 0.012–0.050$, Wilcoxon). With smaller feed force, it was noted that FST in the exposed fingers during HAV exposure (conditions V11 and V51) was significantly less than FST measured during force exertion alone ($p = 0.008–0.031$, Wilcoxon).

Compared to solely hand force exposure, unexposed fingers did not show greater reductions in median FST as a result of vibration exposure.

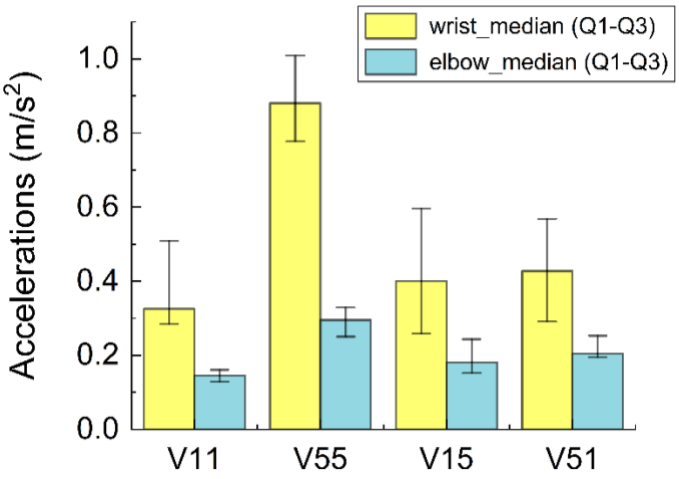


Figure 4-5 The median values of vibration accelerations (m/s^2, r.m.s.) measured at subjects' right wrists and elbows in z_h-axis across four conditions with vibration applied. The upper and lower caps referred to the third quartile (Q3) and the first quartile (Q1) in each condition, respectively.

Figure **4-5** shows the transmitted accelerations to the forearm during HAV exposure with bent-arm posture. Compared to the excited vibration which was 22 m/s^2 r.m.s. measured at the handle, most of the vibration was dissipated or absorbed in the process of transmission. The median magnitudes of the remaining vibration were ranging between 0.33 and 0.88 m/s^2 r.m.s. at the wrist, and between 0.14 and 0.30 m/s^2 r.m.s. at the elbow. It can still be observed that accelerations at the wrist were substantially greater than (about double) those at the elbow, with more evident variations. The total hand-handle forces showed a good linear fit to the transmitted vibration ($p < 0.001$, Spearman). However, no significant correspondence was obtained between either the decrease in %FBF or %FST and the vibration accelerations measured in both locations ($p = 0.063–0.101$, Spearman).

4.9 Discussion

The relationships between FST and force-and-vibration exposure were slightly different from those found for FBF. Both measurement values were manifestations of circulatory effects and can serve as complements and references.

4.9.1 Vascular response to hand force

Hand forces, whether exerted individually or in combination with vibration, resulted in a loss of finger circulation in the exposed hand.

As can be seen within the control group, levels of finger vasoconstriction in exposed fingers were highly dependent on the hand force, which is in contradiction with previous studies in which the hand force had shown little effect on blood circulation (Thompson and Griffin 2009, Ye and Griffin

2009). But the forces applied before were not identical to those used here and the amount of magnitude was negligible. The finding is consistent with earlier studies adopting a gripping position, suggesting that the actual forces acting on the tool handle have an independent impact on the vasculature (Sandover and Louw 1992, Scheffer and Dupuis 1989, Hartung et al. 1993, MIYAKITA et al. 1990). Given the insignificant response of unexposed fingers, such a unilateral reduction is likely resulted from the constriction of local digital vessels by the operating force.

4.9.1.1 grip and feed force

In previous research, the definition of total hand-handle force can be considered in different ways. The coupling force, defined in ISO/WD-15230, was expressed as the sum of the grip and feed forces:

$$F_{coupling} = F_{grip} + F_{feed} \qquad (4-1)$$

where the coefficients before the grip and feed forces both amounted to 1, suggesting there was no difference between the acute effects of grip force and feed force (Riedel 1995). By contrast, the average contact force was characterised as a function of grip force, feed force and handle size, in which the contribution of grip force was greater than that of the feed force (Welcome et al. 2004). The contact force can be written as

$$F_{contact} = \alpha + \beta F_{grip} + \gamma F_{feed} \qquad (4-2)$$

where α referred to the contact force offset due to the handle sensor, and β and γ were constant coefficients, which represented the contribution of the grip and feed force, respectively, depending on the diameter of the handle (Marcotte et al. 2005).

Moreover, the relevant biodynamics studies have found either coupling force or contact force had a considerable influence on the biodynamic response of the hand-arm system. For example, Riedel (Riedel 1995) found the coupling force (20-200 N) can be used to correct the measured weighted root mean square acceleration of the hand exposed to HAV; the result from Marcotte (Marcotte et al. 2005) showed that the coupling force dominated the driving-point mechanical impedance (DPMI) response below 200 Hz, and contact force had a stronger effect at higher frequencies as DPMI was better correlated with grip than feed force above 200 Hz; while Burström (Burström 1997) concluded that a higher level of DPMI was more closely related with an increase in push force. Moreover, the relevant biodynamics research found that the grip force mainly affected the dynamic response of the forearm and the feed force acted on the entire hand-arm system (Adewusi et al. 2010).

In this work, the effect was more emphasised on the vascular system. The result of the control group showed that when the grip and feed force were the same, a larger coupling force would lead to a greater impact on the finger blood flow. While the equal importance of grip and feed force can

be denied when it came to C15 (or V15) and C51 (or V51). More reduction in FBF was found with greater grip force, though the coupling forces were the same, indicating a stronger dependence of vasoconstriction on the grip force. The reason for the stronger influence of the grip force could be the greater contact region between the handle and the fingers. Better tissue–handle interaction with increased pressure thus would compress the digital vessels adequately to cause impairment in circulation. Another possible explanation was that the grip force mainly depended on the muscles of the fingers and palm, but the muscle group involved in feed force may come from the upper arm which might yield different effects on finger circulation.

4.9.2 Vascular response to vibration

As mentioned before, the vibration-induced reduction of FBF was restricted to the fingers receiving the HAV, which was not in agreement with those reported in other studies that the vasoconstriction was observed in both exposed and unexposed fingers (Bovenzi et al. 2000, Bovenzi et al. 2006, Ye and Griffin 2011a), probably because the force effects had some local limits and the intensity of the excited vibration here was relatively low.

After removing the contribution of force, the additional vascular effect of vibration was not significant on FBF. One possible underlying mechanism devoted to the phenomenon is that the soft tissue in the human finger has already been compressed and deformed with the application of force loading and related to a loss of blood permeability (Bader et al. 1986). Extra vibration may cause little further volume change, especially in the case of high gripping forces. At the same time, other systems that contribute to the digital circulation could also be affected during high tissue compression. For example, the sympathetic traffic to and from the fingers can be limited, leading to a reduction in vasoconstriction. The drop in FBF in the right fingers during period 2 with HAV was similar across all the conditions. It cannot be ruled out that vibration may have a certain masking effect on the hand force. Also, the measure of FBF might be partly influenced by artefacts like air cuff and strain gauge which were not in good contact with the test fingers when fingers were constricted and exposed to the vibration.

Although the measure of FST was not as susceptible as FBF to the change of force, it can provide extra evidence of the vibration effect present on exposed fingers, as well as the different influences of grip and feed force. Across control conditions with smaller grip force (C11 and C15), no difference was found between %FST measured during period 2 and period 1, but exposure to conditions V11 and V15 resulted in clear reductions in FST when the vibration was applied. What's more, in the absence of HAV, the significant difference in %FST reduction caused by forces only occurred between conditions with both forces being large and both forces being small (C55 and C11). Whereas in the case of vibration, this difference (between V55 and V11) extended to condition V55

and another condition V15 with less grip force, indicating that the vibration may amplify the effect of the change of grip force.

In this study, there was only one single-frequency HAV with one magnitude which was not able to give a broad conclusion on the HAV effects on exposed fingers. Although previous studies came to the conclusion that higher frequency and greater magnitude of the excited HAV were associated with greater reductions in FBF (Bovenzi et al. 1999, Bovenzi et al. 2000), the impact of hand force should always be involved with respect to the effects of HAV.

4.9.3 Influence of hand force on the response to vibration

It was expected that force applied at the right hand should have a great impact on altering the vascular changes when exposed to HAV, while the additional reductions in FST and FBF caused by the increase of force were not significant.

While it is noted that the impact of hand force on the response to vibration was mainly reflected by the dynamic transmission. The vibration level transmitted from the finger to the wrist and elbow in the forearm was linearly related to the coupling force, partly due to the change in tissue stiffness. Many of the previous HAV models considered vibration transmission as a useful and integral part of defining actual harm to the human body (Saha and Kalra 2016); while this study only found FST had a certain correspondence with the transmitted vibration accelerations. More laboratory investigations are needed to see whether vibration transmitted or absorbed can predict the difference in the vascular result and that predict the actual effect of hand-arm vibration.

4.10 Summary

The combination of grip and feed force had a negative correlation with circulatory disturbances. Force applied alone at the exposed hand would significantly alter the FBF with a reduction of up to 60%, and greater force was associated with more loss of finger circulation, while the additional reductions in FBF and FST caused by vibration were not significant. Based on these findings, the circulatory responses seem to be dominantly regulated by the hand force exposure, indicating that the hand force should be taken into account in the assessment of exposure amount. In addition, the vascular responses seem to be more sensitive to the grip exertions than feed exertions. Indentation measures should be taken to minimise the grip force exerted on power tools as much as possible.

Chapter 5 Experiment 2: Acute neurological responses to force and vibration

5.1 Background and next design

We have learned from the first experiment that the effect of the applied hand force varies and should not be underestimated. Either a hand force applied alone or applied during the HAV exposure leads to a loss in blood circulation. This is consistent with our expectations, as workers tightly grasp the vibration tools in practice, rather than relaxing their hands on the vibrating platform as in the laboratory. The next step is, we would like to investigate whether this sensitivity and response to force are specific to the vascular system alone or if it also affects other interconnected systems, such as the nervous system, and whether this finding could be extrapolated to a wider range of hand forces and vibration intensities.

In the last study, the acute effect of force on the circulatory system appears to be even greater than the effect of vibration. To better understand this, further experiments and analyses need to be conducted to determine if the relatively moderate vibrational level used in the last experiment contributed to this observation. Therefore, in this study, two different vibration levels—one higher than that of the previous experiment and one lower—are selected and compared with a relatively small force to find out their relative importance in regulating human response, especially in the nervous system. For the sake of comparison, only grip force proven to have a pronounced effect is considered here without distinguishing different hand forces.

5.2 Experiment question

The question to be answered by this experiment is: Are the acute impacts on hand nerve function following HAV exposure affected more by the force exertions during exposure rather than vibration?

Various neurological problems are known to occur in individuals occupationally exposed to HAV, and acute HAV exposure is found to have some temporary effects on hand nerve function, such as vibration sensation and thermal sensation. Other than that, a large force exerted during HAV exposure is acting on the vibrating tool, which is likely to be involved in affecting the neural response to vibration.

That is to say, the hand-arm nervous system tends to respond to both the vibration and the force applied during the exposure. On top of that, how firm grasping or being in connection with the vibrating tool decides how much vibration is transmitted into the hand-arm system. Whether the

exerted force has an independent effect on the HAV-induced neural changes? Whether the hand nerve function is more sensitive to the vibration or the force? At present, limited knowledge on how or how much the force works is available. As a result, the aim of the study is to investigate the acute neurological response to different levels of HAV, and the effect of grip exertions on hand nerve function before and after exposure to HAV.

5.3 Experiment hypotheses

- Hand nerve function (finger perception of vibration and temperature) is affected by the exerted force without vibration presented on the hand.
- Hand nerve function is sensitive to the applied force when the vibration amount is small.
- With high vibration levels, HAV rather than hand force dominates the acute sensorineural response.

5.4 Participants

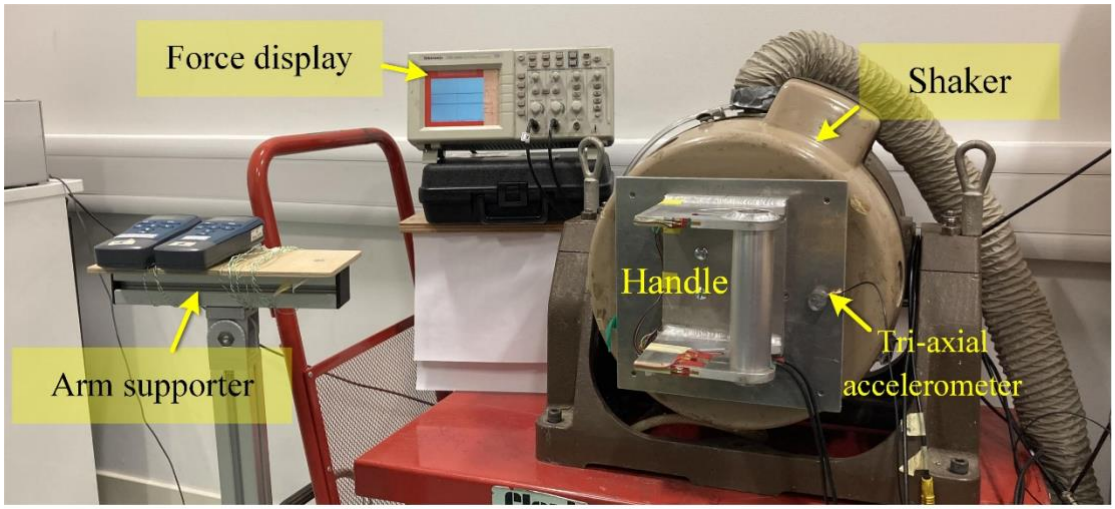
12 healthy male subjects and 12 healthy female subjects were recruited from the University of Southampton. They were screened using a health questionnaire to exclude those occupationally exposed to HAV or whoever suffered from vascular or neurological problems. One of them was a smoker.

Subjects aged between 20 and 33 years (mean 25.8, SD 3.4). Their basic information is listed below in Table **5-1**, in which hand sizes were measured according to BS EN ISO 21420:2020 (ISO 2020). Hand length referred to the distance between the wrist and the tip of the middle finger.

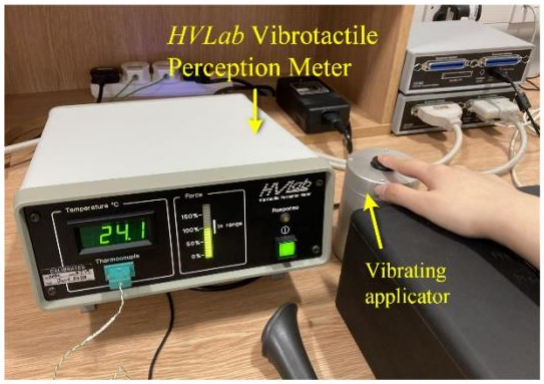
Table 5-1 Subjects basic characteristics.

		Stature (cm)	*Mass (kg)*	*Hand length (cm)*	*Hand circumference (cm)*
Male	mean	173.9 (SD 7.8)	75.9 (SD 9.7)	18.3 (SD 0.7)	20.7 (SD 0.9)
	range	165-194	60-93	17.0-20.0	19.5-23.0
Female	mean	162.4 (SD 5.6)	55.5 (SD 10.1)	16.5 (SD 1.2)	18.4 (SD 0.9)
	range	153-172	44-70	14.2-18.0	17.0-19.5

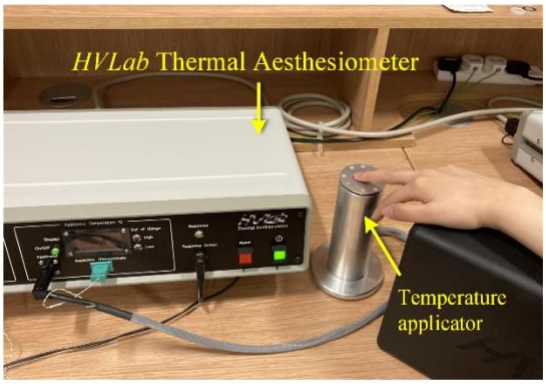
5.5 Apparatus and approaches taken



(a) Experiemnt set-up for HAV exposure



(b) VPT test



(c) TPT test

Figure 5-1 (a) The experiment set-up for hand-arm vibration exposure. (b) The HVLab Vibrotactile Perception Meter being used to test the vibrotactile perception threshold, and the subject's hand posture with the forearm supported during the test (index finger exposed). (c) The HVLab Thermal Aesthesiometer being used to test the thermotactile perception threshold and the subject's hand posture with the forearm supported during the test (middle finger exposed).

The vibration excitation system was the same as the one in the last experiment. A same handle was installed on the vibrator producing the vibration along the z_h-axis to the dominant right hands of the subjects, as shown in Figure **5-1**(a). Grip forces measured by the handle force sensor were displayed on the screen of an oscilloscope in the front, helping subjects maintain them in the desired ranges. To monitor the vibration transmitted to the wrist and elbow, Kionix KXD94 accelerometers were attached to the right upper arm of the subjects.

As specified in Chapter 3, detection of hand nerve function was based on two acute quantitative sensory testing (QST): the vibrotactile perception threshold (VPT) test and the thermotactile perception threshold (TPT) test.

VPT test was executed by the *HVLab* Vibrotactile Perception Meter (VPM) (Figure **5-1**(b)), controlled by the *HVLab* Diagnostic Instruments Manager software, running on a personal computer. The VPM system was made of vibratory modules and response modules. The vibratory modules came supplied with a vibrating probe (a diameter of 6 mm) and a surround (a diameter of 10 mm) at the top of the applicator. The vibration signal at 31.5 Hz or 125 Hz was sent to the probe on which the subject's finger pressed downward to maintain good contact. The force exerted on the surround was measured using strain gauges and feedback was provided by the force meter on the front of the control box. A response button was held on the contralateral hand and going to be depressed as soon as a vibration was felt by the ipsilateral exposed finger. Once the measurement was complete, the mean threshold and the variability were automatically calculated and displayed in acceleration units (i.e. ms^{-2} r.m.s.).

TPT test was executed by the *HVLab* Thermal Aesthesiometer (TA) (Figure **5-1**(c)), controlled by the *HVLab* Diagnostic Instruments Manager software, running on a personal computer. The TA system was also made of vibratory modules and response modules. The vibratory modules came supplied with an applicator which incorporates a Peltier semi-conductor heat pump through which the temperature was provided. The pump was covered by a thin metal contact plate at the top, allowing the subject's finger to rest on that. The reference temperature for both warm threshold (TPTw) and cold threshold (TPTc) tests was set at 32.5°C. A response button was held on the contralateral hand and going to be depressed as soon as a temperature change (either increase or decrease) was felt by the ipsilateral exposed finger. Once the measurement was complete, the warm and cold mean thresholds and the standard deviation were automatically calculated and displayed in degrees Celsius (i.e. °C).

5.6 Motion stimuli and force range

The produced vibrations were sinusoidal acceleration stimuli with a single frequency of 125 Hz since the Pansini channel found to be associated with vibration disorders was sensitive to vibration stimulation around this frequency. The excitation levels of vibration were subject to the ethical considerations. Vibration magnitude ranged from frequency-weighted 1.38 m/s^2 r.m.s. (unweighted 11 m/s^2 r.m.s.) to 5.50 m/s^2 r.m.s. (unweighted 44 m/s^2 r.m.s.).

Subjects were supposed to attend one session with six different force and HAV conditions as shown in Table **5-2** below. HAV was applied to them in four conditions and two other control conditions only had force applied. Each condition involved holding the handle for two minutes. It is designed to reduce the length of time exposed to the stimuli in one go, by having a break of 10 minute or more in between. The excitation levels of vibration were subject to ethical considerations. Both the

magnitude and duration were controlled under the daily exposure limit set by the Health and Safety Executive (HSE), which was presumed not to cause any permanent harm to the subjects.

According to the conclusion of the previous test, it was known that grip force rather than feed force seemed to play a major role in hand strength and its influence, and a relatively large grip force was studied. Therefore, this experiment mainly focused on the grip force and its magnitudes were adjusted to be smaller.

The details of the six conditions were:

Condition 1: 10 N grip force

Condition 2: 10 N grip force + 125 Hz HAV at 11 ms^{-2} r.m.s. (1.38 ms^{-2} r.m.s. frequency-weighted)

Condition 3: 10 N grip force + 125 Hz HAV at 44 ms^{-2} r.m.s. (5.50 ms^{-2} r.m.s. frequency-weighted)

Condition 4: 30 N grip force

Condition 5: 30 N grip force + 125 Hz HAV at 11 ms^{-2} r.m.s. (1.38 ms^{-2} r.m.s. frequency-weighted)

Condition 6: 30 N grip force + 125 Hz HAV at 44 ms^{-2} r.m.s. (5.50 ms^{-2} r.m.s. frequency-weighted)

Table 5-2 The six exposure conditions experienced by participants.

	No vibration	**V1 = 125 Hz HAV at 11 ms^{-2} r.m.s.**	**V2 = 125 Hz HAV at 44 ms^{-2} r.m.s.**
F1 = 10N	F1	F1+V1	F1+V2
F2 = 30N	F2	F2+V1	F2+V2

The amount of HAV exposure corresponded to the *A*(8) value, calculated by:

$$a_{hw(8h)} = \sqrt{\frac{1}{t_t}\sum_{i=1}^{n} a_{rms_i}^2 T_i} \qquad (5-1)$$

where t_t is 8 hours, a_{rms_i} is the frequency weighted HAV magnitude for the condition *i*, and T_i is the exposure period of condition *i*. For this test, the total vibration level applied to each subject was:

$$a_{hw(8h)} = \sqrt{\frac{1}{480}(1.38^2 * 6 + 5.50^2 * 6)} = 0.6340 \text{ ms}^{-2} \text{ r.m.s.} \qquad (5-2)$$

5.7 Experimental procedure

Each subject attended one session lasting less than 2 hours. Prior to the test, subjects were asked to avoid alcohol and tobacco for 12 hours and caffeine assumption for 2 hours before the test to minimise the influence of alcohol, tobacco and caffeine on their blood circulation and neurological perception.

The experiment was conducted at a controlled room temperature of 24 ±2°C (mean 24.69, SD 0.42). Subjects were habituated at room temperature for five minutes before the session began. The rest values of VPT, TPT and the maximal grip strength of each subject's right hand were recorded after the acclimatization, which might take around 4 minutes. During the exposure, participants were asked to take a relaxed upright seating position with left hands supported at the heart level. Their right hands hold an instrumented handle with a bending-arm posture at a similar height (slightly lower), under six force-and-vibration conditions as described in Table **5-2**. In each exposure condition, subjects went through the following periods:

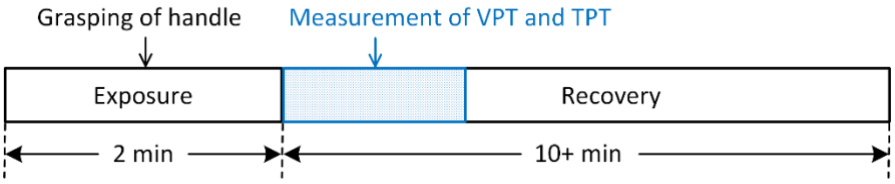


Figure 5-2 Timeline events during one experimental trial. Subjects experienced various force-and-vibration conditions by grasping the handle. The measurement of VPT and TPT after exposure can be regarded as part of the recovery period.

Immediately after the exposure, participants were instructed to release their hands from the handle and underwent the tests of VPT and TPT, followed by an adequate recovery period (10 min for conditions without HAV, 15 min for small HAV and 20 min for large HAV). After that, subjects were allowed to have an extra break and adjust the amount of the next attached force, while keeping sitting comfortably at all times. Different conditions were conducted at random.

These QSTs were done in the order mentioned above (VPT before TPT). VPT was tested by VPM for around one minute at 31.5 Hz and 125 Hz on the right index fingertip. The surround contact force was set at 2N. TPTw and TPTc were tested using TA on the right middle fingertip to avoid the same finger being affected by the VPT test. Accelerations at the right wrist and right elbow were recorded during the exposure period to calculate the transmissibility related to the vibration dissipation or absorption.

5.8 Statistical analysis

Descriptive statistics were initially employed to give an overview of the collected data. Since the results of VPT and TPT (or their TTSs) were not normally distributed, the data were analysed using the non-parametric method in SPSS. The median values of the data gathered on both genders were mainly used as a measure of the overall tendency.

To quantify the significance of the differences in the VPT and TPT, the Wilcoxon matched-pairs signed-ranks were performed between conditions with different hand forces and vibrations. Gender differences were studied based on the Mann-Whitney test. The vibration transmissibility was determined by the amplitude ratio of the input acceleration at the handle to the transmitted acceleration measured by the accelerometers on the forearms. The Spearman correlation analysis of finger sensorineural response and transmissibility was carried out to determine the dependence of hand nerve dysfunction on the absorbed vibration in the forearm. Statistical significance was indicated when the p-value fell below 0.05.

5.9 Results

5.9.1 Hand nerve function during pre-exposure period

The rest levels of VPT calculated for all subjects on right index fingers were centred at 0.13 m/s^2 or 101.97 dB at 31.5 Hz, and 0.22 m/s^2 or 106.97 dB at 125 Hz. Higher thresholds were observed at 125 Hz than 31.5 Hz, which seemed to be in contrast with the equivalent perception threshold contours reported in previous work in which people were found to be more sensitive to HAV at higher frequencies around 125 Hz (Miwa 1967, Morioka and Griffin 2009). Actually, it should be noted that the magnitude of the HAV in the standard was expressed in displacement rather than the acceleration here. The amount of change (TTS) in terms of dB relative to the resting VPT value was studied hereafter so as to avoid misleading. There was no significant difference in relation to gender for the VPT at 31.5 Hz or 125 Hz ($p = 0.198–0.514$, Mann-Whitney).

The median TPT at the middle finger was 35.82°C for the heating test and 29.84°C for the cooling test. Females were more sensitive to the temperature change and had significantly lower warm thresholds (35.0 versus 37.4°C) but not for cold thresholds (29.7 versus 29.8°C).

Neither the maximum grip strength nor BMI was found to be correlated with the thresholds ($p = 0.106–0.783$, Spearman).

5.9.2 Hand nerve function after exposure

The TTS results of vibration sensation at 31.5 Hz and 125 Hz are presented in Figure **5-3**. A similar trend in vibrotactile change can be found between the two test frequencies. Compared to the pre-test, a positive shift of VPT at the right index fingers was observed to occur after the exertion of force for both frequencies. With the vibration applied, all participants suffered from a transient increase in neurosensory threshold, indicating reduced vibration perception after the HAV exposure. The median TTS was 3.4-3.6 dB at 31.5 Hz and 6.9-7.8 dB at 125 Hz for HAV of 11 m/s^2 r.m.s. (unweighted), much more pronounced than control conditions with only force applied. A quadrupling of the HAV magnitude, which was 44 m/s^2 r.m.s. (unweighted), resulted in an even higher threshold in vibration perception than the small amount of HAV for both frequencies ($p < 0.001$, Wilcoxon).

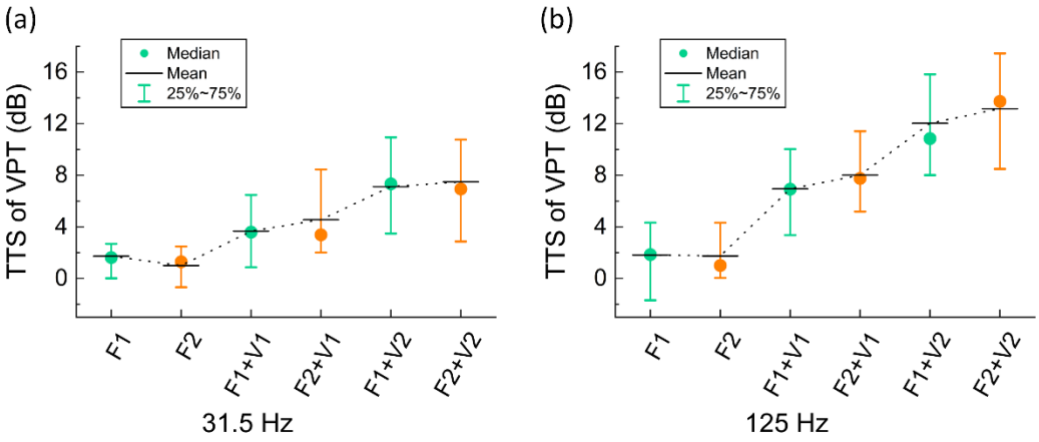


Figure 5-3 Mean and median TTSs of fingertip VPT compared to the pre-exposure at 31.5 Hz and 125 Hz (expressed in dB) for the six force-and-vibration conditions (see Table **5-2**).

The influence of hand force tended to be different in three conditions with and without HAV. No significant differences in TTS at both frequencies were observed in either control conditions or vibration conditions with a higher level of HAV when force increased from 10 N to 30 N ($p = 0.223$–0.648, Wilcoxon). In contrast, for conditions with exposure to smaller HAV stimuli at 11 m/s^2 r.m.s. (unweighted), TTS obtained with greater hand force was significantly higher than that measured with less force, where the change was significant for 125 Hz ($p = 0.028$, Wilcoxon) but not for 31.5 Hz ($p = 0.223$, Wilcoxon). The detailed statistics results of VPT difference comparison under different experimental conditions are shown in Table **5-3**.

Table 5-3 Statistics of Wilcoxon matched-pairs signed ranks test on VPT at 31.5 Hz and 125 Hz. Those with significant differences between the two conditions ($p < 0.05$) are shown against a grey background.

	Rest - F1	Rest - F2	F1 - F2	F1 - F1+V1	F2 - F2+V1	F1+V1 - F2+V1	F1+V1 - F1+V2	F2+V1 - F2+V2	F1+V2 - F2+V2
Sig. (p value) at 31.5 Hz	0.011*	0.032*	0.223	0.002**	0.000**	0.223	0.000**	0.000**	0.819
Sig. (p value) at 125 Hz	0.022*	0.024*	0.648	0.000**	0.000**	0.028*	0.000**	0.000**	0.449

* $p < 0.05$; ** $p < 0.005$.

Non-parametric statistical method was supposed to compare the medians of different samples, but in this study, the changes in mean values of TTS seemed to be more consistent with the statistical results than median values, which was partly due to the different data distribution of different genders. Since the females' data were clustered around a lower threshold than the males' over the different conditions, the median value for both genders alone might not be adequate to report the central change of QST results. Both the mean and median changes were given in the figures for reference.

The TTS results of temperature sensation are presented in Figure **5-4**. It is worth noting that the increment of the cold threshold was plotted in the absolute value of TTS, namely |TTS|, for easy viewing and comparison.

The loss of thermotactile perception was reflected by the positive shifts in warm perception or negative shifts in cold perception. The measurement of TPT was based on the right middle fingertips with a reference starting temperature fixed at 32.5°C. While the fingertip skin temperature differed before the exposure and afterwards, likely to cause some deviation in the shifts. Thus, the thermal neutral zone (TNZ) threshold, which was the difference between warm and cold thresholds, was introduced to better evaluate the temperature neurosensory response to the exposure.

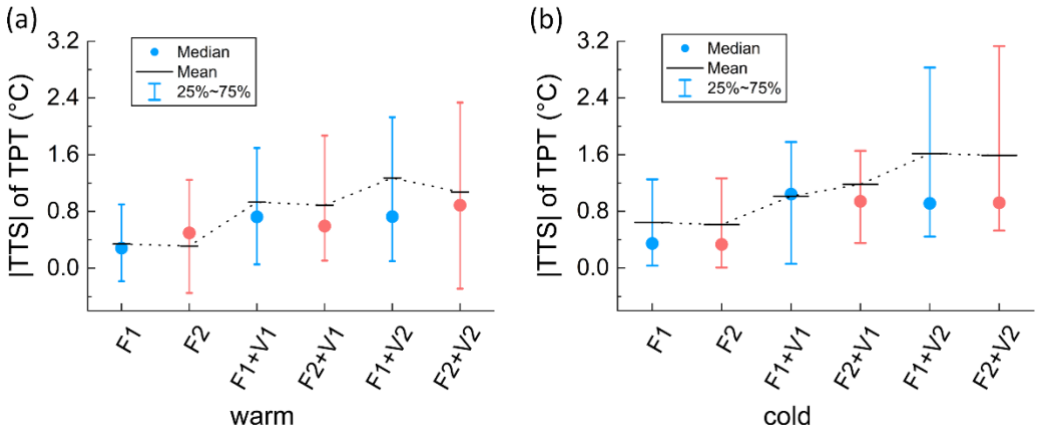


Figure 5-4 Mean and median TTSs of fingertip warm and cold TPT compared to the pre-exposure for the six force-and-vibration conditions (see Table **5-2**).

The Wilcoxon's test revealed that the TNZ after the force applied was greater than that prior to the exposure (p = 0.007–0.012, Wilcoxon). Changes between rest conditions and control conditions were significant for TPTc (p = 0.001–0.002, Wilcoxon) but not for TPTw (p = 0.059–0.137, Wilcoxon). When the HAV was activated, a greater change in TNZ was found for all the conditions exposed to HAV compared to control conditions (p < 0.005, Wilcoxon). There were significantly more shifts in TPT for conditions with small HAV added than without HAV (p = 0.003–0.032, Wilcoxon) except for an insignificant result under cold stimuli between condition F1 and condition F1+V1 (p = 0.445, Wilcoxon). The difference in TNZ due to the increase in the level of vibration was only significant when a small force was acted on the handle, and only the TTS of cold perception was significantly affected by HAV magnitude with a small force.

Table 5-4 Statistics of Wilcoxon matched-pairs signed ranks test on TPT for warm perception, cold perception and neutral zone. Those with significant differences between the two conditions (p < 0.05) are shown against a grey background.

	Rest - F1	Rest - F2	F1 - F2	F1 - F1+V1	F2 - F2+V1	F1+V1 - F2+V1	F1+V1 - F1+V2	F2+V1 - F2+V2	F1+V2 - F2+V2
Sig. (p value) for TPTw	0.059	0.137	1.000	0.016*	0.032*	0.943	0.199	0.297	0.475
Sig. (p value) for TPTc	0.002**	0.001**	0.920	0.445	0.006*	0.161	0.012*	0.134	0.853
Sig. (p value) for TNZ	0.007*	0.012*	0.658	0.014*	0.003**	0.607	0.031*	0.153	0.841

* p < 0.05; ** p < 0.005.

The analysis also showed that the increment of force did not significantly affect the TNZ. The TTS due to the exertion of force did not differ between two control conditions with either 10 N or 30 N. Also, when the vibration level was constant, no reductions in the thermotactile thresholds were observed with the increase of hand force (p = 0.161–1.000, Wilcoxon). The detailed statistics results of TPT difference comparison under different experimental conditions are shown in Table **5-4**.

After adjusting the absolute thresholds, the sensorineural responses of force and vibration for different genders exhibited a similar trend and varied within a similar range (p = 0.453–0.840 for VPT, 0.198–0.291 for TPT, Mann-Whitney).

5.9.3 Associations between hand nerve dysfunction and vibration transmission

Participants had an average grip strength of 394.0 (SD 97.6; range 280-570) N, with males averaging 465.0 N and females averaging 322.9 N. Since the strength of these participants was much less than

that of the workers occupationally holding the vibrating tools, the forces applied here were much smaller than in practice and would not cause the participants any strong sense of discomfort or fatigue. Even with such a small force, the amount of vibration transmitted to the hand-arm system (picked up at the wrist and elbow) was dependent on the force applied. The results of the medians intercept and Inter-Quartile Range (IQR) of accelerations obtained over 24 participants during the HAV exposure were shown in Figure **5-5**.

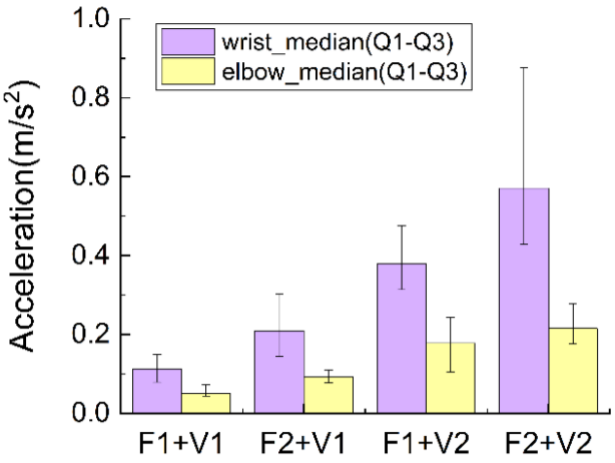


Figure 5-5 The median values of vibration accelerations (m/s^2, r.m.s.) measured at subjects' right wrists and elbows in the z_h-axis across four conditions with vibration applied. The upper and lower caps referred to the third quartile (Q3) and the first quartile (Q1) in each condition, respectively.

The HAV transmissibility generally declined with the increase in distance from the grip point, especially dropping faster at a relatively high frequency like 125 Hz. The transmitted vibration was found to be no more than 0.6 m/s^2 r.m.s. at the wrist and no more than 0.3 m/s^2 r.m.s. at the elbow over all conditions with bent-arm posture. Most of the vibration was primarily limited to the fingers and palm in direct contact with the vibrating handle. However, the remaining acceleration collected at these two locations of the forearm varied similarly under different force and vibration conditions.

The magnitude of the excited vibration substantially affected the transmitted accelerations to the forearm. The median of accelerations almost quadrupled as the HAV magnitude increased by a factor of four under conditions with a small force. Also, the application of force had a high correlation to the transmitted vibration at both locations ($p = 0.000–0.034$, Spearman), though the influence of force might not be linear and the median change between two levels of HAV under a large force was less than 4 times.

In addition, there was strong evidence showing that VPTs at both these two frequencies were well correlated with the transmitted acceleration levels at the forearm ($p = 0.000–0.003$, Spearman), though no significant correspondence was obtained for thermal thresholds. Given the results,

transmissibility can be seen as a useful indicator of assessing the actual harm to the human body ($p = 0.214–0.464$, Spearman).

5.10 Discussion

This study was to investigate the acute neural response to HAV shown in finger QSTs, and to see whether the QST results of HAV were sensitive to the level of grip force applied during the exposure. Arguably, our results can be used to analyse the dominant relationship between force and vibration from a physiological perspective and provide a reference for the allowable range of force and vibration in vibration scenes, in order to reduce the risk of neurological dysfunction.

The different conditions were conducted randomly on the same day. It cannot be denied that the order in which the test condition was given may affect the results because participants were likely to learn from the test and do better over time. Some unintentional improvement in the threshold was noticed during different test periods, which was not caused by the change in the experimental conditions. Those learned shifts in threshold were shared features among subjects, which were not excluded from the results.

5.10.1 The effects of the level of HAV

The application of HAV was found to significantly affect the hand nerve function, which is in agreement to many experimental investigations (Malchaire et al. 1998). Measurements in previous studies were taken after exposure to HAV compared to the rest conditions with no HAV or force, which may be subject to some controversy due to the absence of removing the contribution of hand force in the exposure (Burström et al. 2009). In this aspect, this study introduced control conditions with and only with the same level of force exertion, and investigated the additional effects of vibration. As expected, the results strongly confirmed that vibration had an independent effect on sensory nerves.

Moreover, the QST results were sensitive to the magnitude of vibration, as the greater the HAV magnitude, the more reduction in vibrotactile perception and thermal perception at fingertip ($p < 0.005$), which agreed with those reported by (Harada 1978, Hirosawa et al. 1992, Morioka and Griffin 2002). A possible reason for the effect of vibration could be the loss in tactile sensibility occurred among the mechanoreceptive afferent units that mediate the detection (Lundström 1986). As shown in the result of the acceleration transmission, the greater shifts in VPT and TPT by the high level of HAV were likely attributed to an increase in vibration emission into the hand-arm system (Shibata and Maeda 2008), and thereby lead to more depression of tactile unit activity.

It is well known that different responses can be exhibited based on different testing methods. Both the vibrotactile sensation and thermotactile sensation were detected in this study and it was found that these two QSTs were affected similarly depending on the vibration. The influence on the VPT was not only tested at 125 Hz, the same frequency as for the stimulus, but also at 31.5 Hz, which was much lower than the vibration-sensitive range. The results suggested that the VPT at other frequencies than the stimulus frequency could also respond to the HAV exposure, as revealed by Maeda (Maeda et al. 1995). Measurement of TPT showed an acute extension in TNZ, indicating a reduced TPT sensibility after the HAV exposure regardless of the possible offset of the reference skin temperature. Different conclusions were drawn in previous studies concerning TPT measurement. TTS was only found for cold perception but not for warm perception in Burström's work (Burström et al. 2008) while Löfgren et al. reported that sensation of temperature was significantly improved after exposed to HAV, which probably be affected by the shifts in the FST (Löfgren et al. 2020).

5.10.2 The effects of the level of force

As mentioned above, QSTs were detected for values in control conditions with only the force applied and being compared to the baseline values in resting conditions. The hand force alone could lead to adverse effects on hand nerve function, reflected by a small but significant shift in VPT and a broaden in TNZ, but the measured shifts without exposure to vibration did not differ from each other.

After applying a small HAV, the differences between the VPT acquired at different force levels became statistically significant. The influence on VPT can be associated with the vibration transmission through the hands, pretty much like the HAV effects. A high grip force resulted in an increase of muscle stiffness, allowing more vibration absorbed and transmitted up to the arms (PyykkÖ et al. 1976, Welcome et al. 2004). The tactile receptors could be heavily affected in the process.

The analysis also showed that the measured VPT was dependent on the test frequencies, as VPT at 125 Hz appeared to be more affected than 31.5 Hz with the increase of grip force. In addition, the domination of force seemed to be limited to conditions with a small amount of HAV. With high vibration levels, HAV rather than hand force played a major role in regulating the response in VPT, as altering the grip force was not able to introduce more reduction in vibration perception.

The shifts in TPT due to the different levels of force after exposure to HAV were not as pronounced as VPT. No significant decrease in fingertip thermal perception was induced by the increase of grip force when keeping the HAV level consistent. It can be inferred that the mechanisms of the activation of thermotactile units are not similar to that of the vibrotactile ones. Alternatively, the

test order (VPT before TPT) may be partly responsible for the insignificant results since the influence on the thresholds declines quickly over time.

5.11 Summary

This study examines the acute effect of exposure to HAV on hand nerve function, and the involvement of grip force applied during exposure in the regulation of neural response. The hand nerve function (finger perception of vibration and temperature) was affected by the grip force acting alone, and highly dependent on the level of vibration when a HAV was presented on the hand. When the vibration level was small, the vibratory sensation seemed to be more impacted by the grip exertions than the thermal sensation, indicating that the temporary threshold shift of vibrotactile perception might be more sensitive to the amount of exposure. With high vibration levels, vibration rather than grip force dominated the acute sensorineural response. The influence of force and its relationship with vibration should be further explored and properly considered in vibration scenarios to minimise the risk induced by using vibrating workpieces.

Chapter 6 Experiment 3: Comparison of the acute effects of force on hand vascular and nerve function during the vibration

6.1 Background and next design

It has been known from the first two experiments that both force and vibration contribute to the response to exposure in vascular system and nervous system. And the effects between conditions due to the gender difference are not so significant.

However, we have also encountered somewhat contradictory findings. The first experiment suggested that the circulatory response exhibited higher sensitivity to hand force, whereas the second experiment concluded that the neural response was mainly affected by vibration.

The contradiction drove us to figure out whether this difference is due to inherent differences between the two systems or from variations in exposure conditions. In the second experiment, we utilised a higher level of vibration and reduced the force. So for this experiment, we would maintain the same exposure conditions as the second experiment on nerve system, but focus on examining the vascular responses. By comparing it with the findings of the first two experiments, we hope to further elucidate this disparity and uncover the regulatory relationship between force and vibration.

Furthermore, the hand posture during this experiment would differ from that of the first experiment performed on vascular system. The initial experiment employed a grip posture, whereas in this one, a flat hand posture would be adopted to minimise potential errors resulting from device compression associated with the grip posture.

6.2 Experiment question

As a result, as a comparison experiment for the second experiment, question to be answered by this study is whether there is a coupling between the blood flow system and the nervous system, which of them is more sensitive to exposure conditions, and which exposure factor dominates the response.

6.3 Experiment hypotheses

- The degree of finger vasoconstriction (decrease in finger blood flow and finger skin temperature) would depend on the exerted force, but more sensitive to the vibration level.

- There is certain correlation between vascular system response and nerve system response.

6.4 Participants

Up to 12 male subjects participated in the experiment. All of them were recruited from the University of Southampton. In respect to ethical considerations, the subjects read written instructions and gave informed consent before commencing the experiment which was approved by the Human Experimentation Safety and Ethics Committee at the University of Southampton (ERGO/FEPS/64786). They were screened using a health questionnaire to exclude those occupationally exposed to HAV or whoever suffered from vascular or neurological problems. Prior to the test, they avoided alcohol and tobacco for 12 hours and caffeine assumption for 2 hours to minimise the influence of alcohol, tobacco and caffeine on their blood circulation and neurological perceptions.

Subjects aged between 21 and 32 years (mean 27.0, SD 3.6). They had an average grip strength of 523 (SD 63; range 420–620) N. The mean stature and mean mass of the subjects were 176.8 (SD 4.2; range 170.0–185.0) cm and 78.4 (SD 9.6; range 65.0–100.0) kg. Hand sizes were measured according to BS EN ISO 21420:2020 (ISO 2020). Their mean hand circumference was 20.6 (SD 1.3; range 17.2–21.7) cm, and their mean hand length (distance between the wrist and the tip of the middle finger) was 18.9 (SD 0.6; range 18.0–19.7) cm.

6.5 Apparatus and approaches taken

The experiment was conducted using a same electrodynamic vibrator, Derritron VP30, powered by a 300 W amplifier. The vibrator produced vibration along the vertical axis and was positioned as displayed in Figure **6-1**. Instead of an instrumented handle, a flat plate (contactor) was rigidly fixed on top of the vibrator, on which the hand can place. Subjects were required to press down the plate using their right hands with the bending-arm position. The plate comprised a force sensor (load cell 1022, Tedea Huntleigh, Beit Herut, Israel) for measuring the pushing-down force. The measured forces were displayed on a screen in front of the participants to help them keep the hand forces at the desired levels.

To monitor the vibration transmitted to the hand-arm system, a tri-axial accelerometer (Brüel and Kjær piezoelectric type, Brüel & Kjær, Nærum, Danmark) was placed on the base of the plate measuring the intensity of the excitation, and another two tri-axial accelerometers (Kionix KXD94, Kionix, Ithaca, NY, USA; sensitivity: 200 mV/g; measuring range: ±10 g) were attached at the subject's right wrist and right elbow separately picking up the vibration level.

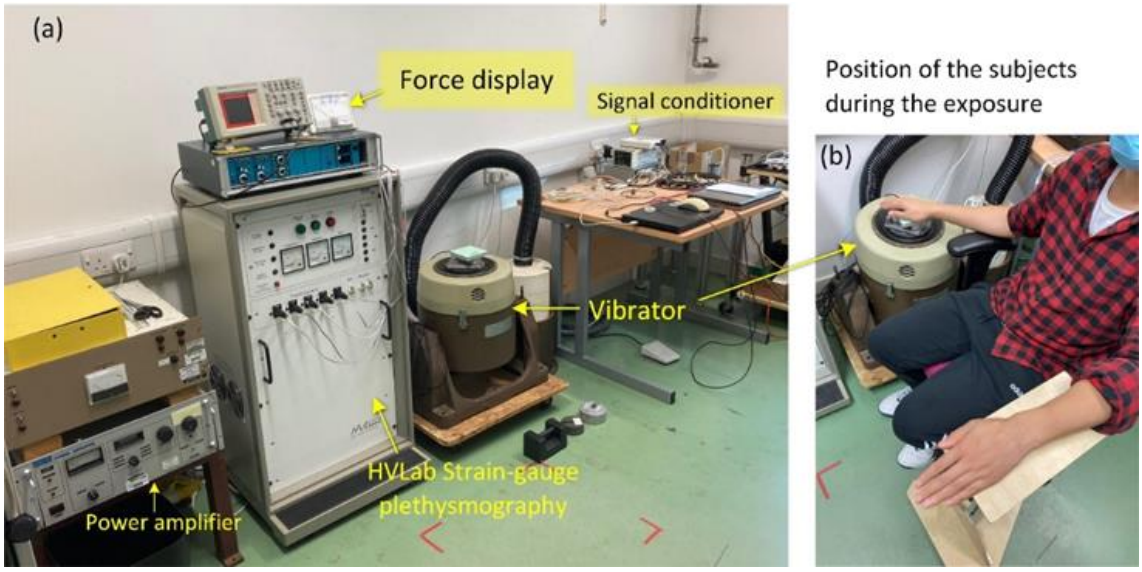


Figure 6-1 (a) The experimental set-up. (b) Position of the subjects when exposed to motion.

Detection on blood circulation was based on two methods of acute measurement: finger blood flow (FBF) test and finger skin temperature (FST) test. Test of FBF was presented on the subjects' both hands by strain-gauge plethysmography as mentioned above. Test of FST was resorting to digital thermometer fastened by micropore tape to the middle phalanx of fingers on the backside. A mercury thermometer displayed the room temperature on its screen with an accuracy of ±0.5°C.

6.6 Motion stimuli and force range

In this study, subjects were required to press down an instrumented plate using their right hands with the bending-arm position, as shown in Figure **6-1**(b). The vibration signals were generated by MATLAB and the HVLab toolbox, transmitted through the contactor and applied to the right hands in the vertical direction. The produced vibrations were sinusoidal acceleration stimuli with a single frequency of 125 Hz as the Pansini channel found to be associated with vibration disorders was sensitive to vibration stimulation around this frequency. Vibration magnitude ranged from frequency-weighted 1.38 m/s^2 r.m.s. (unweighted 11 m/s^2 r.m.s.) to 5.50 m/s^2 r.m.s. (unweighted 44 m/s^2 r.m.s.).

Subjects were supposed to attend one session with six different force and HAV conditions as shown in the Table **6-1** below, each of which involved pushing down the plate for two minutes. HAV was applied to them in four conditions and two other control conditions only had force applied, just like in the second experiment. The total vibration exposure amount was 0.6340 m/s^2 r.m.s. in A(8) value. It was designed to reduce the length of time exposed to the stimuli in one go, by having a break of four minutes or more in between. The excitation levels of vibration, both the magnitude and duration, were controlled under the daily exposure limit set by the Health and Safety Executive (HSE), not known to cause any permanent harm to the subjects. Grip force for the non-HAV

condition was set to be the same as for the HAV condition, either 10 N or 30 N, both of which were small and safe relative to the subjects' muscle strength.

Table 6-1 The six exposure conditions experienced by participants.

	No vibration	V1 = 125 Hz HAV at 11 ms^{-2} r.m.s.	V2 = 125 Hz HAV at 44 ms^{-2} r.m.s.
F1 = 10N	F1	F1+V1	F1+V2
F2 = 30N	F2	F2+V1	F2+V2

6.7 Procedure

The experiment was conducted at a controlled room temperature of 23 ±2°C (mean 22.8, SD 0.8). Subjects were habituated at room temperature for five minutes before the tests begin. After the acclimatization, they did hands-on practice and familiarised themselves with the process of the test. The maximal grip strength of each subject was measured. A hearing protector was required to be worn throughout the test.

During the session, participants were asked to take a relaxed upright seating position with their left arms and hands supported at the heart level. Their right hands experienced a period of nine minutes:

- Period 1: no force and no vibration (3 min): measurement of FBF, FST
- Period 2: force (and vibration) (2 min): measurement of FBF, FST, accelerations
- Period 3: no force and no vibration (4 min): measurement of FBF, FST

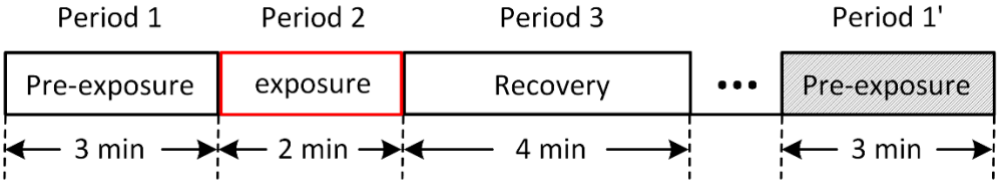


Figure 6-2 Timeline events during one experimental trial. Subjects experience various force-and-vibration conditions during period 2 by pushing down the plate on top of the shaker. Period 1 of the following trial can be regarded as the latter part of the recovery period of the previous round.

During the pre-exposure period, subjects were resting their right hands flat on top of the contactor without applying any force. After that, they applied a downward force with their hands in the same posture as in period 1. For the conditions with vibration present, a 2-min sinusoidal 125-Hz vibration at 11 m/s^2 rms or 44 m/s^2 rms (unweighted) was applied during period 2 followed by a 4-min recovery period. After that, subjects were allowed to have an extra break and adjust the amount of

next attached force, while keeping sitting comfortably at all times. Different conditions were carried out in random order.

Measurement of FBF was taken every 30 s in the right index and fourth fingers, and also in the index, and fourth fingers of contralateral (left) hands. FST was recorded in the middle fingers of both hands before and after the exposure. Accelerations at the right wrist and right elbow were measured during period 2 to calculate the transmissibility related to the vibration dissipation or absorption.

6.8 Data analysis

FBF and its percentage change (%FBF) were introduced to avoid unintentional changes in flow velocity during different test periods, while the absolute value of FST was used directly as the room temperature was controlled. The vibration transmissibility was determined by the amplitude ratio of the input acceleration at the plate to the transmitted acceleration measured by the accelerometers on the forearms.

The data were analysed using non-parametric method in SPSS. To quantify the significance of the differences in the FST and %FBF, the Friedman test and the Wilcoxon matched-pairs signed-rank test were performed between conditions with different hand forces and vibrations. Additionally, the Spearman correlation analysis of finger blood flow and transmissibility was carried out to determine the dependence of vasoconstriction in the fingers on the absorbed vibration in the forearm. Statistical significance was indicated when the p-value fell below 0.05.

6.9 Results

Figure **6-3** below presents the overall pattern of the median and mean values of FBF (expressed as % of pre-exposure) in both hands across the 9-min period and the six exposure conditions.

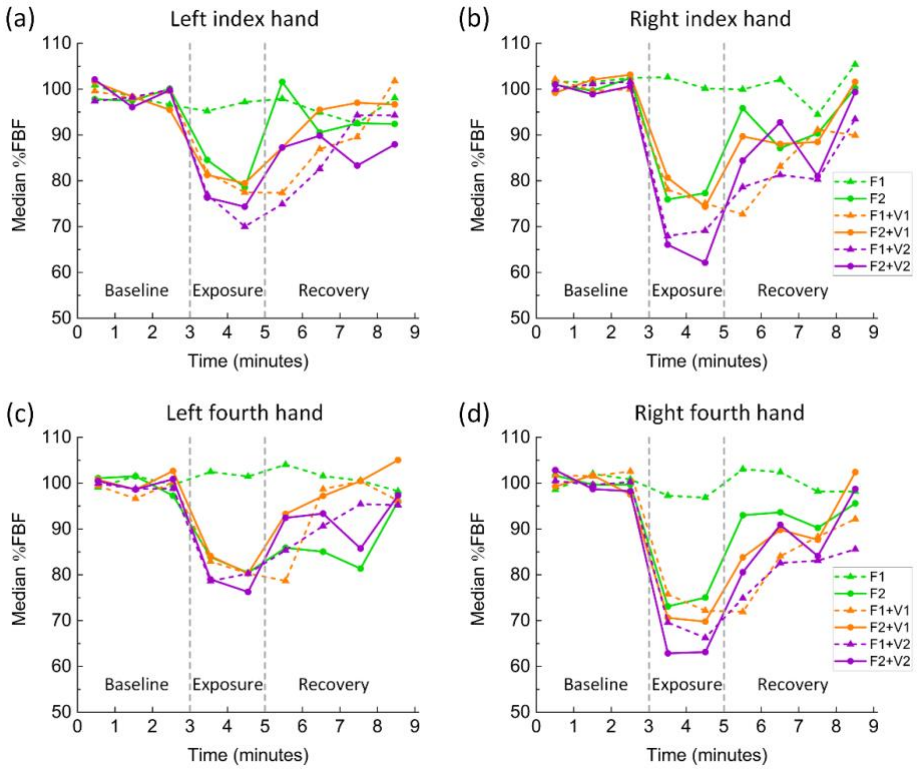


Figure 6-3 Percentage change of finger blood flow (% of pre-exposure) in both hands during six exposure conditions (see Table **6-1**). Plotted symbols are median values. Two dash lines correspond to the time points at which exposure begins and ends, respectively.

6.9.1 Finger circulation during pre-exposure period

During pre-exposure period (period 1), no significant changes in FBF were found for both hands across the six experimental conditions ($p = 0.053–0.883$, Friedman). Over the six measurements before exposure, FBF averaged 2.37 ml/100 ml/s in the right fingers and 2.09 ml/100 ml/s in the left fingers. The rest levels of the right exposed fingers were slightly higher than that of the left unexposed fingers, potentially due to different hand-arm positions. The right hand adopted a bent-arm posture, which is closer to the body, while the left hand extended out and kept flat on the support.

The initial values of FST among subjects varied over the range of 25.8–35.4°C for both hands. As indicated by FBF, the pre-exposure measures of FST in the exposed were higher than that of unexposed fingers (average 32.8°C vs 32.0°C; $p < 0.001$, Wilcoxon). The sets of measures of FST in each condition did not differ during the pre-exposure period ($p = 0.162–0.398$, Friedman).

Notwithstanding the variations in the FBF and FST baselines among different subjects, neither the FBF nor the FST was found to be correlated to the subjects' BMI ($p = 0.051–0.854$, Spearman).

6.9.2 Effects of hand force on finger circulation

As shown in Figure **6-3**, the %FBF reductions were compared along the timeline between two control conditions. Exposure to hand force alone during period 2 induced different FBF responses in exposed right fingers depending on the level of force.

Compared to period 1, the FBF in the right fingers was not affected by a grip force of 10 N ($p = 0.710$, Wilcoxon), and no significant fluctuations were observed in FBF throughout period 2 ($p = 0.555$–0.873, Friedman). While exposure to a greater force of 30 N provoked a significant reduction in FBF (a decrease of 23%), as shown in Figure 4 and Table 2. The blood flow in the right finger saw a steep drop at the trigger time of 30-N force exposure and was in decline over the rest of the exposure period ($p < 0.001$, Wilcoxon).

The left (unexposed) fingers' FBF response to force during period 2 witnessed a less dramatic but identical trend than in the right fingers. Blood flow in left fingers barely changed during a 10 N force application ($p = 1.000$, Wilcoxon) but slipped over time when increasing the force to 30 N ($p < 0.001$, Wilcoxon).

Different outcomes were found regarding the change of the FST, as can be seen in Figure 5 and Table 3. Relative to FST before the force application, both exposed and unexposed fingers did not show reductions in FST as a result of force-only exposure ($p = 0.136$–0.480, Wilcoxon).

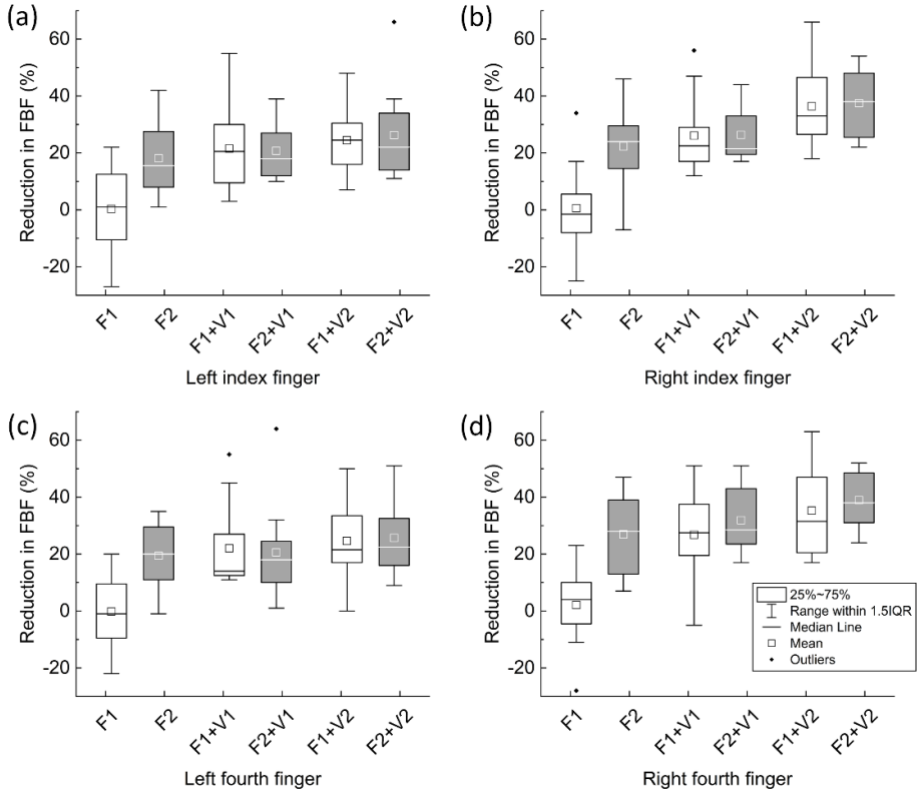


Figure 6-4 Data distribution of the reduction in finger blood flow (% of pre-exposure) of 12 subjects tested in (a) left exposed hand and (b) right exposed hand (average of the index and fourth fingers) during the 2-min exposure to six force-and-vibration conditions.

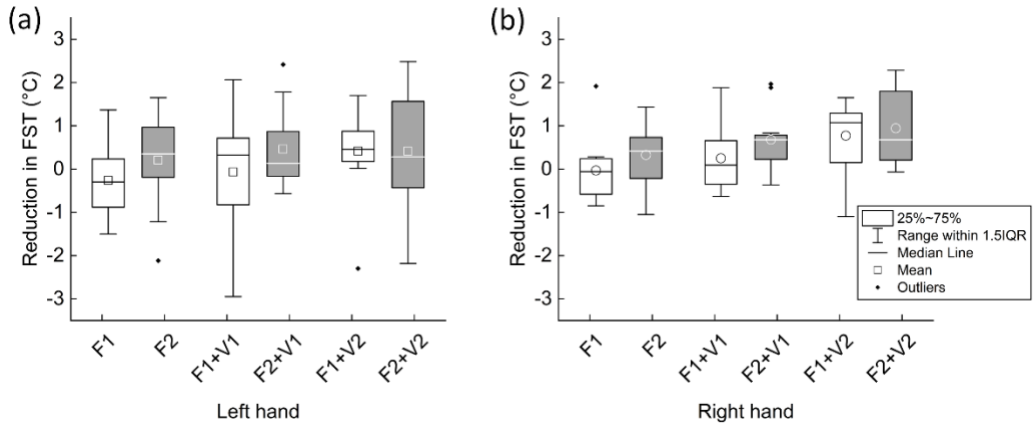


Figure 6-5 Data distribution of the reduction in finger skin temperature of 12 subjects tested in (a) left exposed hand and (b) right exposed hand during the 2-min exposure to six force-and-vibration conditions.

6.9.3 Combined effects of hand force and vibration on finger circulation

Hand force combined with 125 Hz vibration resulted in reduced FBF in both exposed and unexposed fingers, compared to the resting period with no force and no vibration ($p < 0.001$, Wilcoxon). The onset of FBF decline was rapid as soon as vibration exposure began, and the FBF exhibited a downward trend over period 2 with a slow-down rate. This pattern aligned with the FBF changes in the right fingers observed in control cases involving high force level.

Compared to the force-only conditions, the overlay influence of vibration on FBF in exposed right fingers was dependent on the force level. In the presence of low-level vibration (11 m/s^2), a clear decrease in the FBF of right fingers was observed with a 10 N force ($p < 0.001$, Wilcoxon), whereas after a force of 30 N applied, no further reduction in right fingers' FBF was produced as a result of moderate vibration ($p = 0.530$, Wilcoxon). When increasing the vibration level to 44 m/s^2, the dominant effect of the large vibration became apparent, which clearly affected FBF to a larger extent for both force levels ($p < 0.001$, Wilcoxon). The median value of the loss in the blood flow in the vibration group can amount to about 40% of the baseline. The promoting effect of force with HAV applied was different from that when it was exerted alone. The increase in the force level did not lead to more FBF reduction in exposed fingers regardless of the vibration level ($p = 0.376–0.607$, Wilcoxon).

In unexposed left fingers, similar outcomes were found regarding the change of the FBF, as can be seen in Table 2. The Wilcoxon test found that exposure to vibration of 11 m/s^2 during period 2 lessened more FBF in left fingers than in the absence of vibration but only significant when a small force of 10 N was applied ($p = 0.003$, Wilcoxon). The influence of stronger vibration on FBF in left fingers was less prominent than in exposed fingers. At either force condition, no significant difference in FBF was found in the left fingers between the two vibration levels ($p = 0.153–0.587$, Wilcoxon). Moreover, there was not enough evidence indicating that an increase in force level during HAV exposure intensified the decline in FBF in the left fingers ($p = 0.568–0.909$, Wilcoxon).

Regarding the response in FST in the right finger, the contribution of vibration exposure during period 2 seemed to be beyond the limited effect of force alone. Significant FST loss occurred after being subjected to vibration conditions with either stronger force or stronger vibration ($p = 0.004–0.015$, Wilcoxon). Comparatively, the presence of vibration has little effect on the FST of left unexposed fingers. Only in the case where there was a combination of 10 N force and 44 m/s^2 vibration was FST affected ($p = 0.034$, Wilcoxon). For both hands, experiencing a higher-level vibration did not result in more significant reductions of FST than exposure to a low-intensity vibration ($p = 0.568–0.909$, Wilcoxon). Also, similarly to the findings in the response of FBF, an increase in force did not significantly contribute to further declines in FST in both hands when the vibration level remained constant ($p = 0.158–0.814$, Wilcoxon).

Table 6-2 Alterations in finger blood flow.

Percentage change in FBF (% of pre-exposure) for left and right fingers over six exposure conditions; the alterations in FBF were calculated as the differences between the average of median FBF in two fingers of each hand at exposure period 2 and the resting level of FBF during pre-exposure.

	F1	*F1+V1*	*F1+V2*
Left (unexposed) finger	96.89% (90.91–109.74%)	78.38% (64.77–88.91%)	77.65% (69.28–83.62%)
Right (exposed) finger	99.22% (87.92–108.15%)	73.37% (64.09–82.45%)	65.31% (52.16–73.65%)

	F2	*F2+V1*	*F2+V2*
Left (unexposed) finger	79.24% (70.48–85.93%)	80.09% (73.10–85.37%)	77.65% (62.61–82.01%)
Right (exposed) finger	76.71% (63.63–81.96%)	71.18% (59.51–78.31%)	62.30% (51.54–69.86%)

Table 6-3 Alterations in finger skin temperature.

Percentage change in FST (% of pre-exposure) for left and right fingers over six exposure conditions; the alterations in FST were calculated as the differences between the median FST at the first minute during recovery and the resting level of FST during pre-exposure.

	F1	*F1+V1*	*F1+V2*
Left (unexposed) finger	100.88% (99.31–102.71%)	98.98% (97.84–102.49%)	98.64% (96.87–99.46%)
Right (exposed) finger	100.17% (99.28–101.71%)	99.68% (98.00–101.04%)	96.87% (96.18–99.58%)

	F2	*F2+V1*	*F2+V2*
Left (unexposed) finger	98.92% (97.20–100.58%)	99.61% (97.43–100.53%)	98.91% (95.25–101.35%)
Right (exposed) finger	98.79% (97.75–100.85%)	98.03% (97.67–99.32%)	97.99% (94.71–99.33%)

6.9.4 Finger circulation during recovery

Results of FBF from the recovery period was recorded for four minutes. During the recovery period, it seems that FBF in both hands varied systematically across the six exposure conditions.

In the control group, the FBF after the cessation of a small force (10 N) exertion kept steady around the baseline in both right and left fingers ($p = 0.532 - 0.644$, Friedman). As the intensity of force increased to 30 N, the recovery period exhibited a rapid upward fluctuation in FBF of both exposed and unexposed fingers, indicating an ongoing recovery process ($p < 0.001$, Wilcoxon). It was noted that right-finger blood flow hit a low at around the third minute during the rebound process, after which it continued to rise until complete recovery was achieved just as in period 1.

The recovery patterns became more abundant when vibration was present. A gradual blood return in all the fingers was observed in each condition following the HAV exposure. In the case of a small vibration (11 m/s^2), the initial FBF recovery speed in exposed fingers was comparable to that of stronger vibration (44 m/s^2), but with slightly smaller wavering thereafter. An interesting finding is that blood flow recovered more quickly after more intense force application than after small force under either vibration level in both hands. Also, a pullback of FBF occurred before a full recovery to the baseline, which was more pronounced after strong-force exposure.

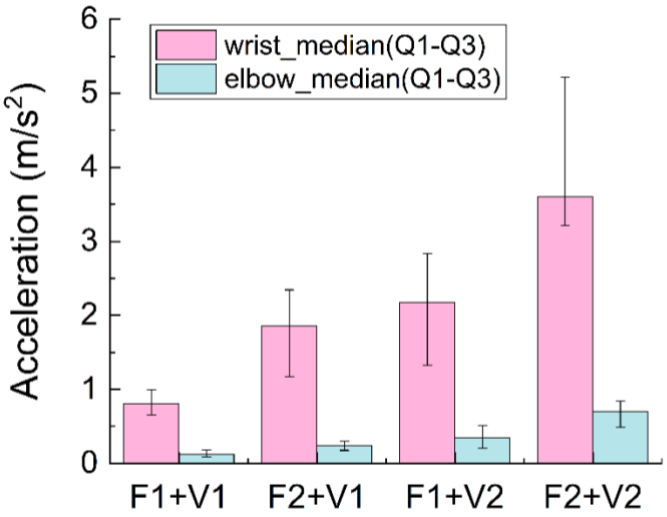


Figure 6-6 The median values of vibration accelerations (m/s^2, r.m.s.) measured at subjects' right wrists and elbows in the vertical axis across four conditions with vibration applied. The upper and lower caps referred to the third quartile (Q3) and the first quartile (Q1) in each condition, respectively.

Figure **6-6** depicts the accelerations picked up at the forearm during HAV exposure while the subjects were pushing down the contactor. The excited vibration (11 or 44 m/s^2) was transmitted up the arm through the contactor. The residual vibration, indicated by the median values, ranged

from 0.81 to 3.60 m/s^2 r.m.s. at the wrist, and from 0.12 to 0.70 m/s^2 r.m.s. at the elbow. This implies that the majority of the vibration was lost or absorbed in the process of transmission. Moreover, the vibration attenuation from the hand wrist to the elbow was substantially greater than that in the previous two experiments, though the locations of accelerations kept the same. A possible reason for the attenuation could be the difference in hand posture and the elevation of the elbow. Despite the low magnitude of transmitted accelerations, the acceleration reading at the elbow, like that at the wrist, showed variation in response to different exposure conditions.

Furthermore, a closer examination reveals a strong linear fit between the hand forces and the transmitted vibration at both locations ($p < 0.001$, Spearman). As the vibration travelled along the forearm, there was a consistent increase in the subsequent transmitted vibration level as the force applied during the HAV exposure increased. However, no significant correspondence was obtained between either the decrease in %FBF or %FST and the vibration accelerations measured at either location ($p = 0.338–0.943$, Spearman). In other words, the transmitted accelerations did not directly align with peripheral circulatory changes, consistent with what we found in the last experiment on vascular response.

6.10 Discussion

In practice, the most common posture for workers employing hand-held vibrating tools is grasping. In this investigation, the hands were held flat. This posture was to eliminate the possible error in the FBF measurement brought on by the compression of the cuff following the grip. The results were contrasted with the outcomes of the experiment involving gripping posture and the results of the two studies had a high consistency.

As can be seen within the control group, only a great force resulted in a loss of finger circulation in the exposed hand when the force was exerted solely. This indicates that the levels of finger vasoconstriction in exposed fingers were highly dependent on the hand force, which is in agreement with the findings in our first experiment. Given that the hand was flat pressed, only the palm of the right hand pressed downward while the fingers remained suspended, such a vasoconstriction was unlikely to result from the constriction of local compression of the device around the fingers. In addition, similar circulatory response patterns were found in the individual fingers on the same side.

What would account for the different performances of two force-only conditions? During the rest period, the right hand was laid down on the conductor in a relaxed state. However, the hand still possessed a certain amount of mass, and paired with the bent-arm position, some residual force would be exerted onto the contactor. As a result, there was little difference between this resting

state and the condition with modest force. Another interesting observation from the timeline was that there was a slight decrease in a row in blood flow in the control condition with a small force. This could probably be attributed to the prolonged immobility of the fingers with the force exertion being too small, as if in the resting state.

In cases where stronger force was required, active participation of the hand was increased. The digital vasculature might experience more deformation, leading to the localised blockage of blood flow. Another possible explanation for the blood flow loss could be the involvement of additional systems in circulatory regulation, such as the active force-induced changes in muscle morphology, or neural activation.

Interestingly, when a comparatively large force was applied alone, the resulting blood flow response in the exposed hand did not differ from that in the presence of moderate vibrations. This indicates that the influence of force should not be underestimated, as it may also increase the risk of compromised blood circulation. Furthermore, this particular pattern of blood flow response was consistently observed in the unexposed left hand, providing compelling evidence of a central sympathetic effect at play.

By removing the contribution of force, the additional vascular effect of vibration was observed significant, which contrasts with our first experiment. Moreover, it was expected that elevated force levels during HAV exposure should amplify the temporary reduction in finger blood circulation. However, no additional reductions in FST and FBF were invoked in this experiment by the increase of force. This is probably because the vibration and force levels chosen in these two experiments were quite different. The first experiment took larger forces and relatively modest vibrations, and this experiment did the opposite. We shall therefore find that the first experiment concluded that the change of force had a greater effect on FBF, while this experiment gave out that the addition of vibrations dominated the vascular effect.

After the exposure stopped, blood flow returned to the finger capillaries, which was denoted as capillary refill (David et al. 2014). Usually, a delay in capillary refill time gives an indication of reduced finger blood circulation. During the recovery period, a distinct rebound in blood flow in all the affected cases, which might be ascribed to the momentary vascular congestion upon cessation of the exposure. However, the effect of the exposure persisted, resulting in a lack of blood supply shown as a notable pullback in the short term. In other studies with longer vibration exposure, not only did the FBF fall back, but the blood vessels contracted more during the recovery period than during the exposure period (Bovenzi et al. 2000). Before blood flow levelling off at the resting level, it seemed that capillary refill took longer after lower-intensity force exposure, but was steadier with smaller fluctuations. This suggested that the degree and speed of vascular congestion were related

to the amount of force applied. The greater the force, the more likely it was that the blood vessels in the palm would undergo sustained deformation, leading to more blood stagnation in certain areas such as the palmar end. Alternatively, it could be subjected to a more pronounced dilation of the blood vessels after the momentary relaxation of a strong force, subsequently affecting the blood flow to the fingertips.

6.11 Summary

Generally, the level of vibration holds a crucial role in determining the acute vascular response, but it is undeniable that the applied force also has an impact.

Hand force exertion alone has varying impacts on blood circulation, with a sufficient force capable of altering the finger blood flow with a reduction of up to 23%. Whereas vibration, particularly at elevated levels, exacerbated acute circulatory disturbances, and predominantly affected the exposed fingers. Interestingly, the extent of digital vasoconstriction did not significantly differ between exposure to larger force alone and exposure to force combined with moderate vibrations. The vascular recovery was also found related to the amount of force applied. Thus, this insight underscores the necessity for further investigations on mitigating the potential adverse effects of vibration while conscientiously accounting for the risk of force.

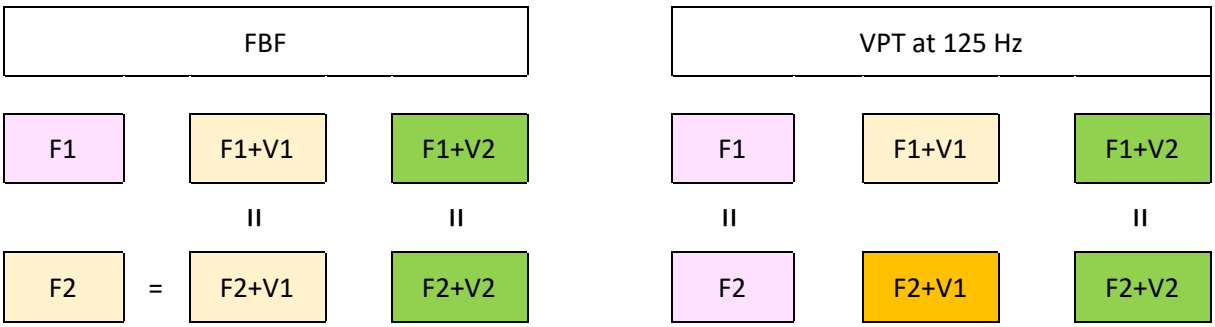
6.12 Summary of the first three experiments

In light of the exploration of the both the response of the circulatory system in this experiment and the response of the nervous system in the previous experiment in Chapter 5, some conclusions can be drawn. Under almost the same force-and-vibration exposure conditions:

- Vascular response: FBF was more sensitive to changes in force and vibration than FST, with the right exposed hand more sensitive than the left unexposed hand.
- Neural response: VPT was more sensitive to changes in force and vibration than TPT.
- Neural responses were more sensitive to changes in vibration magnitude than vascular responses.
- Neural responses were more sensitive to changes in force level than vascular responses when vibration was present.
- Vascular responses were more sensitive to changes in force level than neural responses with no vibration applied.
- Neural response VPT was better correlated with the transmitted vibration at the forearm than TPT and vascular responses.

Overall, both systems were influenced by exposure to vibration and force. The acute effects on the nervous system were statistically more significant than on the blood flow system, where the response in VPT was the most sensitive to stimuli. Therefore, when studying and quantifying the effects of short-term force-and-vibration exposure on human physiological mechanisms, testing of VPT is likely to provide the most discerning differences in results and the most representative trends. Table **6-4** illustrates the differences between the results of each experimental condition. Same colours indicate no significant difference between the adjacent responses, while different colours indicate significant differences between the responses.

Table 6-4 Comparison of results of two responses under the same six force-and-vibration conditions based on statistical analysis. FBF results are from the second experiment and VPT results are from the third experiment.



Chapter 7 Experiment 4: Quantification of the dependence of acute neural response on the force and vibration

7.1 Background and next design

Based on the first three performed experiments and the discussion in Chapter 6.9.2, we have confirmed that the human body responds to the effect of both force and vibration levels. Moreover, we have observed that the intensity of these two factors significantly influences the overall response. Building upon this knowledge, our upcoming experiment is designed to delve deeper into the intricacies of force and vibration by expanding and refining their respective values. We seek to unravel and quantify the dependency of acute human response on these two factors.

Considering the selection of dependent variables, we have discovered that the neural response is an ideal choice. It has been found that acute vascular and neural responses to force-and-vibration exposure share a similar trend and maintained a correlation in between, with the neural response, especially the vibrotactile perception threshold being more sensitive to small variations in exposure conditions. As a result, this study was to capture and analyse the vibration sensory as the primary indicator of human response, investigate how the acute vibrotactile threshold shifts after HAV exposure were in relation to four force levels and five vibration levels, and establish a corresponding empirical relationship formula model that can be applied.

It is worth mentioning that the duration of exposure in the last two experiments was limited to two minutes, which may be somewhat short for the full manifestation of the post-effects. To better derive the cause-effect relationship, the exposure time was extended to three minutes in this experiment.

7.2 Experiment question

What is the dependence of the temporary shift of the vibration perception threshold on the different levels of force and vibration, and to what extent does the level of force or vibration dominate the change of the threshold?

7.3 Experiment hypotheses

- Greater vibration and greater hand forces on the vibrating handle would increase the risk of a decline in neurological perception, with comparatively high vibration levels being more crucial for regulation than hand force.

- There may be an upper limit to the temporary sensorineural threshold where more exposure could not cause further threshold shifts.

7.4 Participants

Up to 15 male subjects participated in the experiment. All of them were students from the University of Southampton. In respect to ethical considerations, the subjects read written instructions and gave informed consent before commencing the experiment which was approved by the Human Experimentation Safety and Ethics Committee at the University of Southampton (ERGO/FEPS/71800). They were screened using a health questionnaire to exclude those occupationally exposed to HAV or whoever suffered from vascular or neurological problems. Prior to the test, they avoided alcohol and tobacco for 12 hours and caffeine assumption for 2 hours to minimise the influence of alcohol, tobacco and caffeine on their blood circulation or nerve functions.

The mean stature and mean mass of the subjects were 176.5 (SD 7.7; range 165.0-185.9) cm and 73.8 (SD 12.4; range 58.0-100.0) kg. Hand sizes were measured according to BS EN ISO 21420:2020 (ISO 2020). Their mean hand circumference was 20.3 (SD 1.1; range 16.7-20.9) cm, and their mean hand length (distance between the wrist and the tip of the middle finger) was 18.9 (SD 1.1; range 19.0-22.0) cm.

7.5 Apparatus and approaches taken

As in the second experiment, this experiment was conducted using an electrodynamic vibrator, Derritron VP30, powered by a 300 W amplifier. The shaker produced vibration along the vertical axis and was positioned horizontally as displayed in Figure **7-1**. An instrumented cylindrical vibrating handle of 40 mm diameter was fixed to the shaker. The measured forces in the handle were low-pass filtered and displayed on a screen in front of the participants to help them keep the hand forces within the desired ranges.

Figure 7-1 The experimental set-up.

There was a tri-axial accelerometer (Brüel and Kjær piezoelectric type) placed on the base of the handle measuring the magnitude of the vibrational excitation. Whilst the other two tri-axial accelerometers (Kionix KXD94) were attached to the subject's right wrist and right elbow separately measuring the transmitted vibration. The accelerometers weighed around 5g, light enough that they would not affect the movement of the arm.

Test of the vibrotactile perception threshold (VPT) was executed by the *HVLab* Vibrotactile Perception Meter (VPM). The vibration signal at 125 Hz was sent to the probe on which the subject's finger pressed downward to maintain good contact. Once the measurement was complete, the mean threshold and the variability were automatically calculated and displayed in acceleration units (i.e. ms^{-2} r.m.s.).

Test of finger skin temperature (FST) was resorting to a digital thermometer fastened by micropore tape to the middle phalanx of fingers on the backside. A mercury thermometer displayed the room temperature on its screen with an accuracy of ±0.5°C.

7.6 Motion stimuli and force range

The produced vibrations were sinusoidal acceleration stimuli with a single frequency of 125 Hz. Five levels of hand-arm vibration (HAV) stimuli were used as exposure conditions: V = 0 (control), 5.5, 11, 22 and 44 in the unit of m/s^2 (unweighted), together with four levels of grip force applied: F = 10, 20, 40 and 80 in the unit of N. Subjects were supposed to go through all force-and-vibration conditions, each of which involved holding the handle for three minutes. It was designed to reduce the length of time exposed to the stimuli in one go, by having a break of 10 minutes or more in between. The excitation levels of vibration, both the magnitude and duration, were controlled under the daily exposure limit set by the Health and Safety Executive (HSE).

7.7 Procedure

Different exposure situations were conducted in a randomised manner. Each subject attended several sessions on five different days, each one lasting around 1.5 hours. The average vibration exposure amount was 0.5011 m/s^2 r.m.s. in A(8) value each day. Prior to the test, subjects were habituated at room temperature for five minutes before the tests begin. After the acclimatization, they did hands-on practice and familiarised themselves with the process of the test. The rest value of VPT and FST, as well as the maximal grip strength of each subject, were measured.

During the session, participants were asked to take a relaxed upright seating position with their left arms and hands supported at the heart level. Their right hands hold an instrumented handle with bending-arm posture at a similar height (slightly lower), under 20 force-and vibration conditions as described.

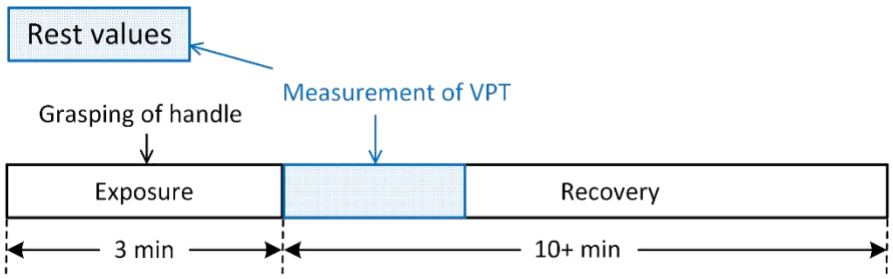


Figure 7-2 Timeline events during one experimental trial. Subjects experienced various force-and-vibration conditions by grasping the handle. The measurement of VPT after exposure can be regarded as part of the recovery period.

Immediately after the exposure, participants were instructed to release their hands from the handle and underwent the tests of VPT, followed by an adequate recovery period (10 min for conditions without HAV, 15 min for small HAV and 20 min for large HAV). After that, subjects were allowed to have an extra break and adjust the amount of the next attached force, while keeping sitting comfortably at all times.

FST was recorded in the middle fingers of both hands after each exposure. Accelerations at the right wrist and right elbow were recorded during the exposure period to calculate the transmissibility related to the vibration dissipation or absorption.

7.8 Data analysis

Descriptive statistics were initially employed to give an overview of the collected data. Since the results of VPT (or TTSs) were not normally distributed, the data were analysed using the non-

parametric method in SPSS. The median values of the data gathered were mainly used as a measure of the overall tendency.

To quantify the significance of the differences in the VPT, the Wilcoxon matched-pairs signed ranks were performed between conditions with different hand forces and vibrations. The vibration transmissibility was determined by the amplitude ratio of the input acceleration at the handle to the transmitted acceleration measured by the accelerometers on the forearms. The Spearman correlation analysis of finger sensorineural response and transmissibility was carried out to determine the dependence of hand nerve dysfunction on the absorbed vibration in the forearm. Statistical significance was indicated when the p-value fell below 0.05.

7.9 Results

The 15 subjects were healthy men aged between 23 and 41 years (mean 31.2, SD 4.7). They had an average grip strength of 537 (SD 70; range 400–650) N. The experiment was conducted in a clinic at a controlled room temperature of 22 ±2°C (mean 22.4, SD 1.50).

7.9.1 Initial values before exposure

The initial values of VPT and FST varied among different subjects, but neither VPT nor FST was found to be correlated to the subjects' BMI ($p = 0.240–0.751$, Spearman).

On the right index finger, the baseline of VPT calculated for all individuals averaged 0.183 m/s^2 at 125 Hz. Before each exposure condition, this value was re-measured to ensure there was no significant deviation. In light of the results, the fluctuation of the initial value was observed no more than 15%, which was regarded as being within the normal range. The amount of positive shift (TTS) relative to the resting VPT values was studied hereafter, indicating a reduced vibration sensation after the exposure. More shift is believed to be associated with a stronger adverse neural effect.

The baseline of FST for all subjects was 33.3°C for the right middle fingers and 33.0°C for the left middle fingers. Change in FST was denoted as △FST, calculated by subtracting the post-exposure FST from the initial one. More reductions in FST indicated poorer blood circulation after the exposure.

7.9.2 Neural response after exposure

Figure **7-3** below shows the median values of TTS of vibratory sensation tested at 125 Hz at the exposed right index finger after exposure to 20 conditions, and the median values of the transmitted acceleration at the wrist during the exposure.

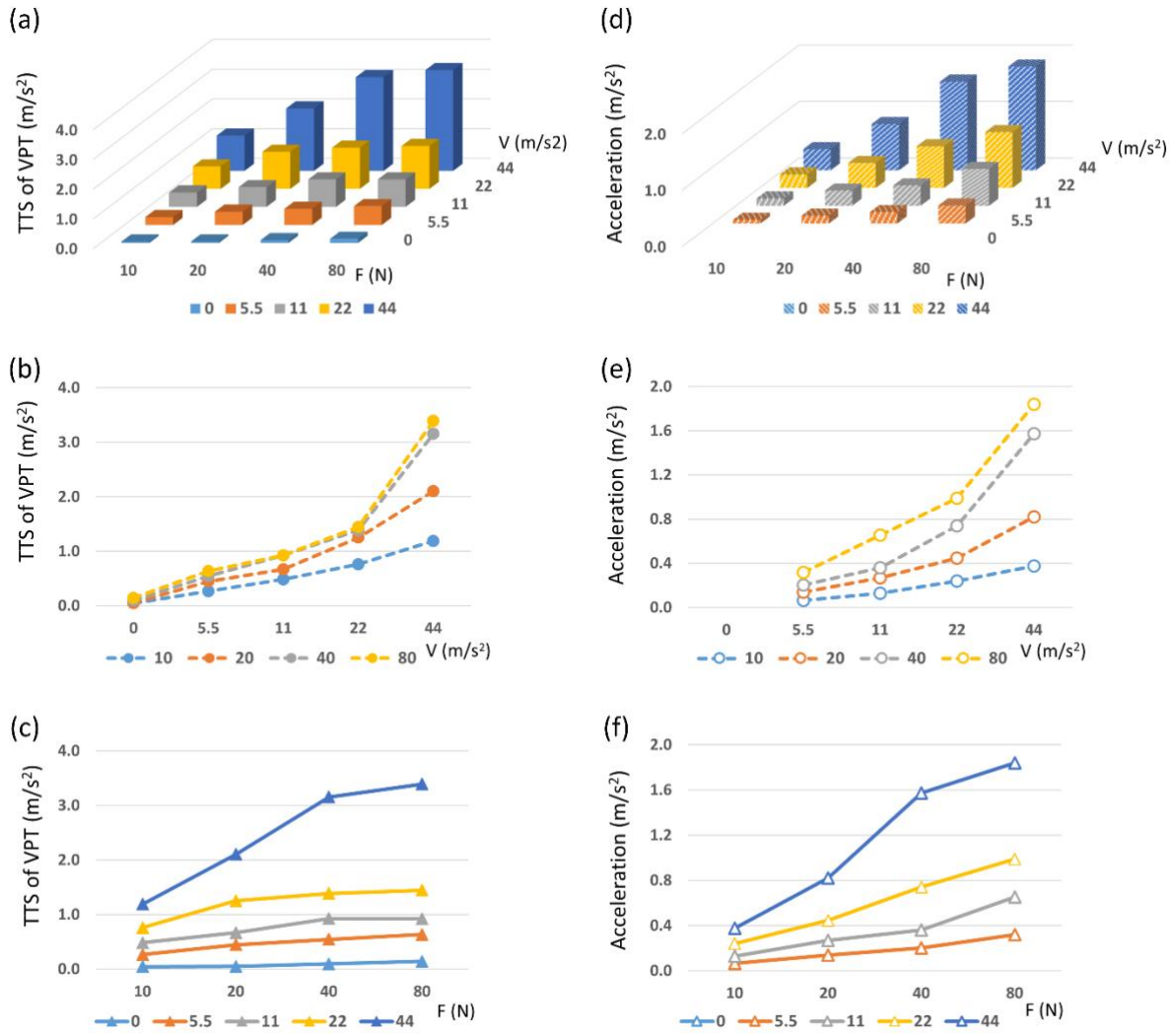


Figure 7-3 Comparison of the trend of the median TTS of vibratory sensation of 15 subjects tested at 125 Hz at the right index finger after a 3-min exposure to different levels of grip force and vibration with the median wrist acceleration of 15 subjects during the exposure. (a) TTS as a function of force and vibration; (b) TTS under five vibrations; (c) TTS under four forces; (d) acceleration as a function of force and vibration; (e) acceleration under five vibrations; (f) acceleration under four forces. V = 0 m/s^2: control condition with no vibration exposure.

Exposure to hand force alone resulted in a minor yet significant shift in VPT in comparison to the baseline (median = 1.6–3.8 dB; $p < 0.001$, Wilcoxon). When the vibration was present, all individuals experienced a transient rise in the sensorineural threshold. Compared with force-only conditions, the shifts in VPT became greater, and were sensitive to the magnitude of vibration. For a small amount of HAV of 5.5 m/s^2 r.m.s. (unweighted), the median TTS was 6.8–13.3 dB, significantly higher than the force-only control conditions ($p = 0.001$, Wilcoxon). Significant differences in TTS can be identified for all five vibration settings regardless of the force level ($p = 0.001$–0.002, Wilcoxon). In response to an increase in vibration level by a factor of 2, the variations in threshold nearly doubled each time. At a maximum vibration level of 44 m/s^2, the median increase in VPT

reached 1.188 to 3.391 m/s^2. As supported by the statistics, there were significant differences between perception reduction under any two vibration magnitudes. The detailed outcomes of the VPT comparison under different vibration situations are displayed in Figure **7-3**(b) and Table **7-1**. Asterisks (*) indicate statistical significance at the 5% level and double asterisks (**) at the 0.5% level. And the results showed a good correspondence to accelerations transmitted to the hand wrist.

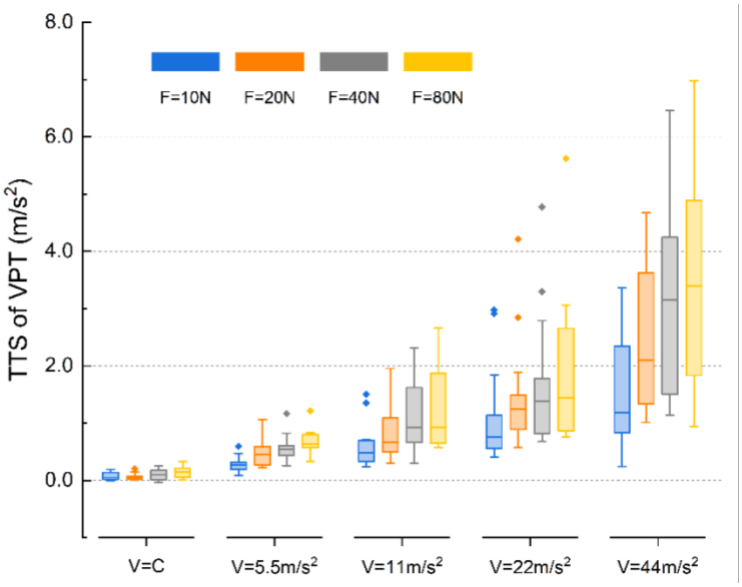


Figure 7-4 Data distribution of the shifts in vibration perception of 15 subjects tested at 125 Hz at the right index finger after a 3-min exposure to 20 force-and-vibration conditions.

The impact on TTS from the force level appeared to vary in conditions with and without HAV. In the absence of vibration, the elevated VPTs were similar between modest force levels (p = 0.125–0.650, Wilcoxon) but significantly different between two big force settings (40 N and 80 N; p = 0.041, Wilcoxon). When the vibration was applied, there were greater TTS differences across four force conditions. Stronger hand forces were associated with more shifts in VPT (p = 0.001–0.006, Wilcoxon) as shown in Figure **7-3**(c). This is especially noticeable when the vibration was strong. Strong vibration combined with small force appeared to induce fewer shifts than when the force was greater but the vibration was only half as much. The TTS results were well correlated with the transmitted acceleration levels at the wrist as well. Exceptions are at high force levels, as according to the statistical analysis, the force increasing from 40 N to 80 N yielded similar results at higher vibration levels (≥ 11 m/s^2) (p=0.078–0.173, Wilcoxon). It seemed that for each vibration level, there was a threshold beyond which further increase in force could not induce more VPT shifts.

Table 7-1 Median values of TTS of vibratory sensation after different exposure conditions. TTS values are in the unit of m/s^2, against a white background. Statistics (p values) of Wilcoxon matched-pairs signed-ranks test on VPT are listed between conditions against a grey background, marked in blue with p<0.05 and marked in red with p≥0.05.

V (m/s²) / F (N)	Control		5.5		11		22		44
10	0.046	(0.001**)	0.266	(0.002**)	0.484	(0.001**)	0.759	(0.001**)	1.188
	(0.650)		(0.001**)		(0.001**)		(0.001**)		(0.001**)
20	0.050	(0.001**)	0.446	(0.001**)	0.667	(0.001**)	1.251	(0.001**)	2.103
	(0.125)		(0.006*)		(0.006*)		(0.006*)		(0.001**)
40	0.095	(0.001**)	0.544	(0.001**)	0.926	(0.002**)	1.386	(0.001**)	3.155
	(0.041*)		(0.004**)		(0.078)		(0.307)		(0.173)
80	0.142	(0.001**)	0.633	(0.001**)	0.924	(0.001**)	1.446	(0.001**)	3.391

*: $p<0.05$; **: $p<0.005$.

7.9.3 Vascular response after exposure

The finger skin temperature changes (before-after) in both hands were less responsive than VPT changes. FSTs declined after any of the exposure. In the case of small force (≤ 20 N), △FST seemed to slightly augment with increasing vibration, though the △FST differences between strong vibration conditions (≥ 11 m/s^2) were not significant at 20 N. With more force applied, the statistical results revealed that no significant further temperature change was found due to a rise in vibration levels.

The median FST reduction brought by different force conditions varied a lot. When the hand force was applied alone, FST in the right hand gradually dropped from 0.6 to 2.0 with the increase of the force from 10 N to 40 N, showing a strong dependence of FST on the force. A maximum of △FST of the right hand was basically reached after exposure to a force of 40 N, and forces rising from 40 N to 80 N did not cause more temperature loss. With vibration loading on, the FST line of the right middle finger with respect to force was not much diverged.

A similar course was followed in the left fingers, though the falling temperature in the left finger was somewhat less pronounced: a remote effect was indicated. The detailed outcomes of the FST comparison under different force-and-vibration situations are displayed in Table **7-2** and Table **7-3** for both hands.

Overall, FST showed a stronger association to force level than vibration level, which significantly differed from the neural response. Statistically, there was no significant correlation between changes in FST and nerve alterations following various exposures ($p = 0.127–0.348$, Spearman).

Table 7-2 Median values of reduction in FST of right middle fingers after different exposure conditions. FST reductions are in the unit of °C, against a white background. Statistics (p values) of Wilcoxon matched-pairs signed-ranks test on FST are listed between conditions against a grey background, marked in blue with p<0.05 and marked in red with p≥0.05.

V (m/s²) / F (N)	Control		5.5		11		22		44
10	0.6	(0.944)	0.7	(0.195)	0.9	(0.575)	1.0	(0.711)	0.9
	(0.010*)		(0.017*)		(0.004**)		(0.017*)		(0.008*)
20	1.1	(0.660)	1.4	(0.232)	1.7	(0.752)	1.4	(0.842)	1.4
	(0.019*)		(0.009*)		(0.556)		(0.208)		(0.124)
40	1.9	(0.533)	1.9	(0.571)	2.1	(0.494)	1.9	(0.660)	1.8
	(0.361)		(0.494)		(0.753)		(0.307)		(0.278)
80	2.0	(0.801)	2.2	(0.205)	2.1	(0.313)	2.1	(0.888)	2.1

*: p<0.05; **: p<0.005.

Table 7-3 Median values of reduction in FST of left middle fingers after different exposure conditions. FST reductions are in the unit of °C, against a white background. Statistics (p values) of Wilcoxon matched-pairs signed-ranks test on FST are listed between conditions against a grey background, marked in blue with p<0.05 and marked in red with p≥0.05.

V (m/s²) / F (N)	Control		5.5		11		22		44
10	0.3	(0.479)	0.3	(0.198)	0.3	(0.379)	0.3	(0.634)	0.4
	(0.035*)		(0.010*)		(0.067*)		(0.141)		(0.032*)
20	0.4	(0.682)	0.4	(0.292)	0.6	(0.140)	0.5	(0.174)	0.6
	(0.129)		(0.168)		(0.052)		(0.060)		(0.327)
40	0.4	(0.014)	0.5	(0.706)	0.5	(0.377)	0.6	(0.599)	0.7
	(0.106)		(0.277)		(0.044*)		(0.213)		(0.324)
80	0.8	(0.431)	0.8	(0.362)	0.8	(0.431)	0.7	(0.916)	0.8

*: p<0.05; **: p<0.005.

7.10 Discussion

This study was to investigate the cause-effect relationship between force and vibration and their acute physiological response. By quantifying this relationship, a better understanding could be

gained of the circumstances where force and vibration dominate the response and determine their respective importance. An empirical model would then be developed in Chapter 8 and enable us to establish guidelines for their practical application and mitigate associated risks.

In line with the previous neural experiment, subjects demonstrated improved performance over time, leading to better vibration sensation during the pre-test period. To ensure consistency, all subjects underwent sufficient training and familiarisation with the measuring devices prior to the start of the tests. Moreover, the exposure conditions for forces and vibrations were conducted at random to try to maintain unbiased conditions.

Although this is primarily a study of nervous system responses, FST measurement holds two significances in this study. Firstly, it allows for the comparison of response results between the two systems to identify coupling or divergence. Secondly, FST was found to affect neural thresholds (Harazin and Harazin-Lechowska 2007). It is then crucial to ascertain whether the change of threshold after exposure is directly caused by variations in exposure conditions, or indirectly influenced by the decrease in FST. According to the statistical analysis, the differences in FST between most cases in this experiment were non-significant, indicating that FST had minimal effect on the thresholds. Therefore, the deviation in vibrotactile thresholds can primarily be attributed to the direct changes in force and vibration conditions rather than fluctuations in finger temperature.

7.10.1 Vibration effects

Excluding force as one of the factors applied during the exposure, vibration resulted in a clear loss in vibration sensation, consistent with our previous tests (chapter 5, Experiment 2). Regardless of the force level, the VPT results were sensitive to vibration intensity; the higher the HAV intensity, the more shift in vibrotactile perception at the fingertip, as was previously documented in previous studies (Harada 1978, Thonnard et al. 1997). As the exposure conditions were refined in this experiment, a nearly linear relationship was observed between VPT shift and vibration intensity, at least up to an intensity of 44 m/s^2. However, it remains uncertain whether this loss of perception will continue with the increase in vibration level or reach an upper limit at some point.

Our previous neural experiment discovered a correlation between the vibration transmitted to the forearm and the alteration in the neural threshold. In this experiment, we examined the outcomes and found that raising the excited vibration level led to increased vibration being received by the forearm and a corresponding rise in threshold shift, and the overall trends in between were remarkably similar. This further supports the hypothesis that the shift in the threshold, reflecting mechanoreceptor activity suppression, is closely related to the amount of vibration received.

7.10.2 Force effects

As a result of force-only exposure, VPT experienced small but significant changes, suggesting that hand force alone may have a negative impact on hand sensorineural function. A similar influence due to the pure force on blood circulation and sensorineural functions has been found in the previous three studies. The combination of force and vibration led to more shifts in the VPT. With the increase of force (10 N to 40 N), the change in VPT follows an upward trend, similar to the effect of the vibration level (Hartung et al. 1993, Löfgren et al. 2020, Nishiyama et al. 1996). In the case of significant vibration, reducing the force can effectively reduce both threshold deviation and vibration transmission.

It is worth noting that a further increase in the large hand force (40 N to 80 N) was unable to introduce more reduction in vibration perception at high vibration levels. This indicates that once the force reaches a sufficient level, further force increments have a limited effect. The additional force may not be able to cause more hand deformation or increased muscle stiffness, thereby limiting the transfer of vibration and preventing further threshold shifts. Moreover, the effect of force is not entirely independent of vibration. With moderate vibrations, additional force still has a significant effect. However, in the case that both vibration and force are at high levels, VPT was only substantially affected by the vibration.

Compared to the previous experiments, this study extended the exposure time. Existing literature highlights the influence of duration on threshold shift, with longer exposures resulting in greater shifts (Malchaire et al. 1998, Burström et al. 2009). The threshold deviation in this experiment was not considerably more than in the previous experiment due to the increase in duration. But the difference in TTS results caused by variations in force was significant. This suggests that the increase in exposure time may amplify or emphasise the effect of force.

7.11 Fitting model

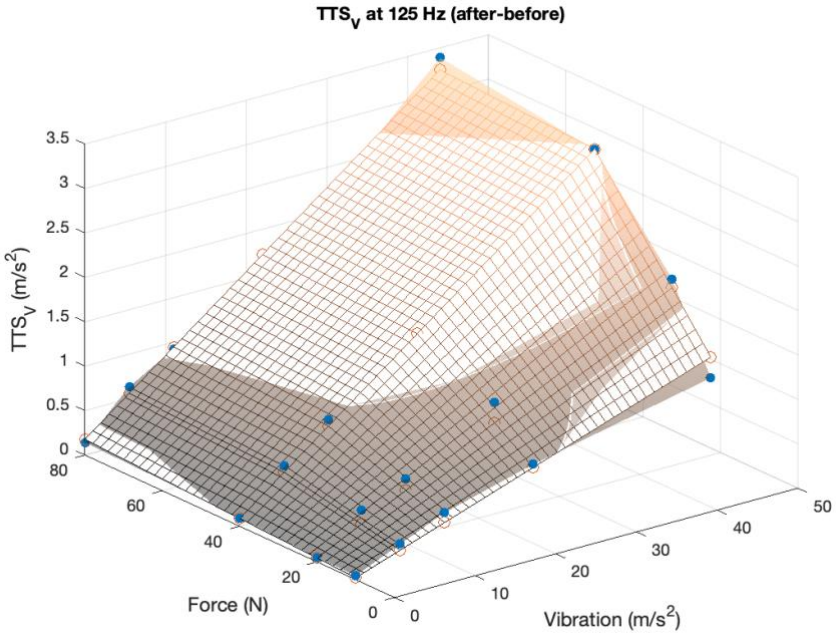


Figure 7-5 Fitting of the neural response results. Blue scatters are median values of TTS test results of VPT measured in the last test.

We have plans of establishing a mathematical model combined with vascular and nervous system components according to the experimental results and investigating the coupling and cooperation between each system when exposed to hand-arm vibration. Although many hand movement models and HAV experiments have been published separately in recent years (Wheatland et al. 2015), few efforts have been made in finding the combination and mutual verification of the models and HAV experiments. Thus, measurements taken here will help to collect and process personal data to validate the model that accounts for the acute effects and even chronic effects, i.e., the presence of the hand-arm vibration syndrome.

Figure **7-5** here displays a numerical fitting based on the median TTS values of VPT (m/s^2) from this experiment. The shift could be treated as a function of force and vibration level:

$$TTS_V = \begin{cases} a * (V + b) * \dfrac{(F + c)}{(40\ N + c)} - a * b * \dfrac{c}{(40\ N + c)} & F \leq 40\ N \\ a * (V + b) + a * b * \dfrac{(F - 40)}{(40\ N + c)} - a * b * \dfrac{c}{(40\ N + c)} & F \geq 40\ N \end{cases} \quad (7.1)$$

Table 7-4 Coefficients for the fitting function.

a	0.0699	
b	1.7348	m/s^2

c	15.0819	N

Where F is the force level in the unit of N, V is the unweighted vibration level in the unit of m/s^2, and the corresponding TTS_v is the derived temporary shift in the vibrotactile perception threshold in the unit of m/s^2. The mesh surface is a graphical representation of the fitting formula, which accords well with the original data marked as blue scatters. It reflects the relationship between the timely response to both the force and vibration levels and can be used to quantify the contribution of the force to the defined exposure amount. Further correction and optimization would be required for a more complete model that includes the components of various systems.

Based on our current model, there are some thoughts on where the result of the vibration perception threshold will go if the two-dimensional graph coordinates (x: force level and y: vibration magnitude) are further extended.

Considering the current trend, a further increase in force may result in no more reduction in vibration perception. However, if the vibration level keeps increasing, it appears that the threshold maintains an upward trend, no matter whether this trend follows a linear, hyperbolic, or exponential pattern after optimization. Therefore, when the vibration reaches a sufficiently high level, does the threshold approach infinity? In other words, does perception completely disappear after extreme HAV exposure?

Due to ethical limitations, we are unable to conduct human experiments with extremely high vibrational levels. It is possible that individuals may not feel any sensation in such cases, but whether this occurs or not depends on various factors such as personal tolerance.

It is worth mentioning here the mechanism behind the reduction in vibration perception. The tactile system is responsible for the sense and process of the vibration signal, allowing the human to feel the mechanical stress. A small magnitude of vibration elicits the tactile response, but there is a threshold beyond which more vibration may lead to an adverse effect. The tactile system may weaken the activity of the receptors or suppress perception. This phenomenon is known as ‘vibration-induced suppression’. It acts as a self-protective mechanism to prevent excessive vibration from harming the tactile system. Then why does the long-time exposure to vibration still cause irreversible effects despite this protective mechanism? One acceptable explanation is that the damage exceeds the system’s capacity for repair. Another reason could be sense adaption, where the tactile system gradually becomes less responsive to the vibration, leading to a diminished ability to perceive and discriminate tactile sensations, even after the exposure has ceased.

Returning to the issue at hand, there might be two cases here when responding to exceptionally high vibrations. The first one is, as long as the duration is short enough, the neural response will get recovered no matter how strong the vibration is. In this case, the ability to perceive is present but depressed. The maximum increase in the VPT depends on whether it is fully suppressed or highly suppressed. The second one is, the vibration, though within a short period of time like a shock-type, could be fierce enough to cause irreversible damage to the tactile system, such as micro-injury to cells or nerve endings. In this way, the damage incurred surpasses the system's inherent capacity for repair, and the resulting shifts in the threshold become more challenging to quantify and assess accurately.

Not to mention that the response depends on the individual variability, as some people may be more tolerant than others. Generally, the activity of the tactile system may be largely affected, but is unlikely to vanish completely, making it difficult to determine an exact threshold for complete loss of perception.

7.12 Summary

Generally, it is concluded that the finger perception thresholds of vibration tend to rise as a function of vibration intensity and hand force level. The results strongly confirmed the great influence of vibration on sensory nerves and underlined that the regulation role of force applied, particularly at high vibration levels, should not be underestimated.

Chapter 8 General discussion and summary

The aim of the project, in a word, is to combat the development of HAVS. The mechanisms responsible for the HAV-induced effect at the hand, the interactions between different affected systems that are not taken into account and how to examine by simulation are of interest here. There are restrictions upon conducting experiments on patients who have been exposed to HAV for a significant length of time. It is possible, however, to explore the acute human response to short-term HAV through laboratory investigations. Since hand force applied during HAV exposure is likely to be one of the most influential factors involved in the human responses but not well studied, the questions to be answered in this research are focused on:

- Whether a hand force acting alone can produce a response similar to that of a vibration?
- With an HAV applied, whether the force participates in the regulation of human response; if so, at which level can force play a major role rather than vibration?
- Whether the effect of the change in force is linear under different levels of HAV, or whether its effect is limited by other factors?

Insight of this, experiments are planned out on how and how much the force and vibration work by looking at the acute HAV effects during and after healthy subjects grasp and push an instrumented handle (or press down on a vibrating contactor) under different combinations of force loadings and vibration.

8.1 Experiment findings

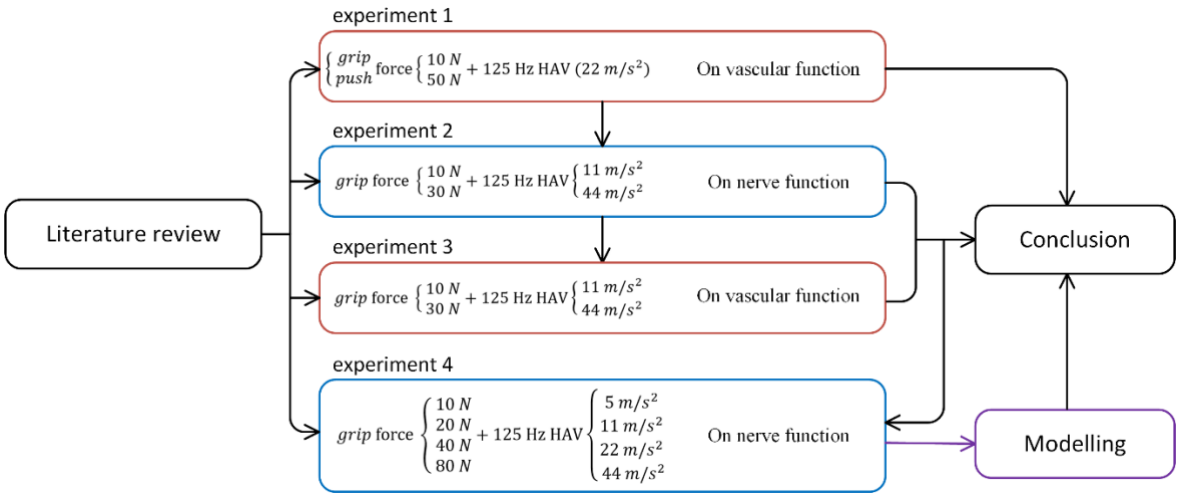


Figure 8-1 Flowchart of the completion of the project plan: the comprehensive framework for four experiments.

A total of four experiments have been finally conducted. Figure **8-1** illustrates the comprehensive framework that encompasses and summarises the key components of these four experiments.

The analysis of the first experiment was focused on the vibration-induced vascular effect which was reflected by the weakening of the peripheral blood circulation such as reductions in FBF and FST. Generally, it was found that hand force played a more important part in circulatory effects than vibration as hand forces resulted in clear reductions in FBF and FST whether the force was exerted solely or combined with vibration. While the additional reductions in FBF and FST from vibration were not significant though only one vibration level was included. Additionally, a larger grip force could lead to a greater impact on the circulation than push force.

For the second experiment, the neurological effect (temporary shifts in vibration and thermal perception threshold) was investigated after exposure to vibration and force. A strong influence by the vibration levels was attained during the course and the neurological response was dependent on hand force when the HAV was small but not for large vibration. Arguably, based on the results of these two tests, the alterations in response in both vascular and nerve systems were evident as a consequence of force when vibration was less than 22 m/s^2 r.m.s., while vibration might dominate the effect roughly at or above 22 m/s^2 r.m.s.

In the third experiment, further measurement of the acute vascular response to short-term HAV was performed. Participants experienced a similar experimental procedure with the same combinations of force loadings and vibrations as in the second experiment but with a slightly different posture. It was expected to find some couplings in temporal variations between nerve functions and vascular functions with regard to the effect of force and vibration. Combining the results of these two experiments, it can be found that there seems to be a correlation between the two systems. Both systems were sensitive to these two factors, with their responses being more apparent as vibration and force intensified. Notably, the nervous system displayed a higher sensitivity to vibration compared to the circulatory response. This is particularly evident in the vibration sensation, which also experienced significant reduction as the force increased in the presence of vibration.

The last experiment still dealt with the short-term effects of vibration exposure with force loadings. It was designed to refine the exposure conditions and quantify the cause-effect relationship between different levels of force and vibration stimuli and the acute human physiological response. Both factors were expanded to a larger scale to assess the relative significance of regulating physiological responses. Temporary shifts in vibration perception thresholds were employed as a representative of the responses for comparative analysis. A fitting of the response results is given below. Also, as mentioned above, many of the previous hand-arm vibration models take

transmissibility as the only consideration, indicating that the vibration transmitted is a useful and integral part of defining the actual effect of hand-arm vibration (Saha and Kalra 2016). In our experiments, some validation tests have been carried out by measuring the transmission of vibration from finger to forearm, but the transmitted vibration level was only found to be associated with neural response, while there was no strong evidence that the transmitted vibration was in relation to the vascular response except for the FST in experiment 2. This could be because the mechanisms behind the two systems are different after force is affected. In addition to receiving increased vibration level after a stronger force (similar to the nervous system), applying force can also directly compress the local blood vessels, leading to circulatory changes. The correlation between transmissibility and vascular or neuro results needs further study to give a basic idea of whether the vibration absorbed can predict the difference in the result and that predict the actual harm to the human body.

The findings bring us back to the raised questions:

- Whether a hand force acting alone can produce a response similar to that of a vibration?

The hand force acting alone could lead to adverse effects on both vascular function, reflected by a significant reduction in FBF and FST, and hand nerve function, reflected by a significant shift in VPT and a broaden in TNZ. The responses in these two systems aligned with those induced by vibration, and were consistent with earlier studies adopting a gripping position (Sandover and Louw 1992, Scheffer and Dupuis 1989, Hartung et al. 1993, MIYAKITA et al. 1990). With the increase of force level, stronger responses occurred in both systems, again similar to the effect of the level of vibration.

The force threshold for triggering such responses has not been extensively discussed, possibly because in real-life tool scenarios, the applied force tends to be substantial. The results of our experiments provided some insights to complement prior research. Earlier studies revealed that exerting a force of 2 N to 10 N to the palm or thenar eminence in a flat hand position did not alter the blood flow but a force of 20 N did lead to changes (Thompson and Griffin 2009, Ye and Griffin 2009, Griffin et al. 2006). In the case of finger exposure, a force application of 2 N to a single finger resulted in decreased blood flow (Bovenzi et al. 2006), whereas 10 N had no effect when all the fingers are exposed (Bovenzi et al. 2000, Bovenzi et al. 1995a). In our investigation of grasping posture, a 20 N grip demonstrated a considerable decrease in blood flow. The nervous system displayed greater sensitivity, as even a 10 N grip induced small yet significant changes in sensation. While these outcomes may be influenced by the duration of exposure and system of action, it becomes evident that the effects of force application are akin to that of vibration.

It's worth noting that responses to force exposure were observed mainly in the hand where the force was applied unilaterally. In the contralateral hand, the effect was not as apparent, and only a consistent change trend in FBF in both hands was observed in experiment 3. This indicates that force might have a relatively localised influence, and more evidence is required to compare it in contrast to the potential central sympathetic mechanisms of vibration.

- With an HAV applied, whether the force participates in the regulation of human response; if so, at which level can force play a major role rather than vibration?

It was expected that force should have a great impact on the regulation of physiological response, wherein the level of force should alter the vascular and neurological changes induced by HAV. However, the effect of force varied between the vascular system and the nervous system.

For the vascular system, the additional reductions in FST and FBF caused by the increase of force were not readily significant, except for experiment 1, which revealed a maximum decrease in FST under the exposure of the highest level of forces. This might be attributed to the relatively limited range of force changes explored in our experiments. By contrast, high-level vibration (above 22 m/s^2) dominated the vascular response as it caused significantly more FBF and FST attenuation compared to force-only conditions and low-level vibration conditions.

The effect of applied force on FBF changes during vibration received little attention. Regarding the change in FST, studies have reported different conclusions on the contribution of force. In Hartung et al.'s research, an increase in grip force correlated with the decrease of FST when the vibration was present, but this effect plateaued beyond 30 N (Hartung et al. 1993). Conversely, another work demonstrated that a greater grip exertion during the HAV exposure led to increased FST and a lowered thermal perception threshold. Additionally, quite a few studies found that FST did not exhibit significant changes when subjected to static force and vibration (Bovenzi et al. 1998, Bovenzi et al. 1999, Bovenzi et al. 2000).

On the other hand, the nervous system showed a clear response to force with the presence of vibration at the vibration perception threshold of 125 Hz. As force level during HAV exposure increased, the change in VPT followed an upward trend, in agreement with previous studies (Hartung et al. 1993, Löfgren et al. 2020, Nishiyama et al. 1996).

In cases where stronger force was required, active participation of the hand was increased, producing an effect incorporated with both active force application and passive vibration induction. The greater propagation of vibrations might be partially responsible for the shift in VPT seen during high-force exposure. Another possible explanation could be the involvement of neural activation.

Generally, the role of force in regulating responses during vibration was evident, but its specific impact could vary depending on the system being examined. Regardless of the differences in sensitivity, both systems were responsive to force which potentially related to real physiological harm.

- Whether the effect of the change in force is linear under different levels of HAV, or whether its effect is limited by other factors?

The relationship between force-and-vibration exposure and physiological response could be complex and multifactorial. According to the findings of several experiments, the responses were positively correlated with force level, but not strictly followed a linear pattern.

8.2 Limitations

The experiments exhibit limitations primarily in two aspects: the exposure conditions, and the methods for measuring the response.

Firstly, the experiments only focus on a single-frequency sinusoidal vibration at 125 Hz, which indeed holds representativeness. However, it is essential to acknowledge that the influence of force on physiology responses under broadband or time-varying vibration signals, may be distinct from those observed under a singular frequency sinusoidal vibration. Additionally, the effect of force might undergo significant fluctuations during unconventional vibration signals such as shocks, potentially yielding disparate outcomes.

Furthermore, the exposure duration remains relatively short for all the experiments. It is plausible that if the exposure time were extended, the cause-effect relationship pattern could undergo alterations, which might be affected by other factors like fatigue. Consequently, any derived relationship curves and formulas need to be critically examined over extended periods of time.

Regarding the method for measuring the response of the vascular system, the current implementation employs a strain gauge plethysmography to measure the overall digit blood flow. However, the utilization of techniques like Doppler metering and blood flow meter with thermal diffusion probe could offer insights into more nuanced alterations, such as those occurring in smaller superficial capillaries. Nevertheless, it is important to note that the Doppler meter must be used under motionless conditions and might be applied to the left unexposed (contralateral) fingers.

In terms of the neural response measurements, namely the tests of vibration thresholds and temperature thresholds, the potential influence of finger temperature should be considered. The experiments discovered that FST decreases following HAV exposure. Currently, it is challenging to

ascertain to what extent the vibration-induced reduction of the threshold is indirectly affected by the concurrent decrease in FST.

8.3 Possible areas for future work

Major advancements have been made in the research of hand-arm vibration (HAV) and its effects on performance and health in people. However, there are still some limitations in our understanding of HAV, and several potential research areas can be explored in the future.

Individual variability. There are some other factors listed in the Annex of ISO standard 5349-1 that are likely involved in the human response to HAV, and individual variability is one of them. People with different ages, genders, genetics, and pre-existing health constitutions vary in their susceptibility to HAV-induced health effects. Future studies could delve into these factors to identify specific biomarkers or genetic markers linked to HAV susceptibility. For instance, studying the expression of specific genes that affect vascular or neurological function could help explain why certain individuals are more vulnerable to HAV-induced syndrome or carpal tunnel syndrome. Personalised risk assessment and tailored treatment for those exposed to HAV may be derived from an understanding of these individual variances.

Mechanisms of HAV-induced health effects. The underlying biological mechanisms by which exposure to HAV leads to health effects are not yet fully elucidated. Investigating the physiological systems and pathways affected by HAV may continue to be the subject of future study. For instance, a study of the systematic coupling between vasculature, peripheral nerves, musculature and the skeletal system might help unravel the complex mechanisms involved. Advanced imaging techniques like ultrasound or MRI could be utilised to assess structural changes or alterations in blood flow resulting from HAV exposure. These studies could reveal the cellular and molecular mechanisms underlying HAV-induced health risks and guide the development of targeted therapies or preventive measures.

Emerging technologies and interventions. Technology is advancing quickly, opening up new possibilities for identifying and reducing HAV exposure. Future research could explore the effectiveness of emerging technologies, such as wearable devices, sensor technologies, and virtual reality (VR)-based training programs. Wearable devices equipped with accelerometers can track HAV exposure in real-time, enabling workers and employers to spot high-risk activities and improve workflow procedures. Sensor technologies embedded in tools or machines can gather data on vibration levels to help monitor and assess the exposure amount. Additionally, VR-based training programs can simulate working environments, allowing workers to learn skills that minimise HAV

exposure. Evaluating the feasibility and impact of these novel approaches could enhance current practices and improve workers' safety.

Intervention effectiveness. Although there are guidelines and control measures in place to mitigate HAV exposure, the effectiveness of these interventions in a practical working scene is not well-documented. Future studies might assess the effectiveness of various engineering controls, personal protective equipment (PPE), and working practices in lowering HAV exposure and related health hazards. For example, comparative studies could be conducted on different anti-vibration gloves or tools designed to minimise HAV transmission. Although it is the last step to protect workers, its benefits and role should be maximised.

Appendix A Participant Information Sheet

Here, only the instruction to subjects in experiment 1 reported in Chapter 4, is provided as an example. Participant information sheets of follow-up experiments are similar.

Study Title: Acute effects of force and vibration on finger blood flow and finger temperature

Researcher: Shuxiang Gao

ERGO number: 55633

You are being invited to take part in the above research study. To help you decide whether you would like to take part or not, it is important that you understand why the research is being done and what it will involve. Please read the information below carefully and ask questions if anything is not clear or you would like more information before you decide to take part in this research. You may like to discuss it with others but it is up to you to decide whether or not to take part. If you are happy to participate you will be asked to sign a consent form.

What is the research about?

The research is for a PhD dissertation. The purpose of the research is to investigate the acute change in finger circulation during and after exposure to combined vibration and force. This study will also investigate the transmission of vibration from finger, palm through arm. This study will provide further understanding on how vibration and force affect the workers occupational exposure to hand-held tools. Also, this study will provide guidance to tool manufactures and users on the suitable active force applied while using hand-held vibrating tools to minimise the negative impact.

Why have I been asked to participate?

You have been selected for this experiment as you are between the age of 18 and 50 years inclusive, with no self-reported working history of hand-held vibration tools.

What will happen to me if I take part?

1. You will be required to complete a consent form and health questionnaire. The questionnaire is designed to assess any hand-arm vibration history and eligibility for participation.

2. You will be asked to avoid alcohol and tobacco for 12 hours and caffeine assumption for 2 hours before the test to minimise the influence of alcohol, tobacco, and caffeine on your blood circulation. Your maximal grip strength will be measured to give an idea on how much grip force you have.

3. You will attend one session (around 1.5 hour) with your right hand exposed to 10 combined vibration and force stimuli conditions. Each stimulus lasts less than 5 minutes. For each condition, you will grasp a handle using different grip (less than 50% of max grip strength) and push forces (less than 50N) with bending-arm position. A sinusoidal 125-Hz vibration at 0.6522 ms−2 rms (A(8) value) will be applied to the handle. For testing you are asked to take a relaxed upright seating position with arm and hands supported at the heart level.

4. To monitor the vibration transmitted to your forearm, two small accelerometers weighted around 5g will be positioned at your right wrist and right elbow separately. They are light enough and will not affect the movement of your arm. During and after exposure to motion, your finger skin temperature will be recorded with digital thermometers attached to your fingers every minute. The change in your digital circulation will be recorded every 30s using venous occlusion plethysmography. The digit flow will be collected via HVLab Multi-channel Plethysmograph (https://www.southampton.ac.uk/hvlab/diagnostic-inst/multi-channel.page). During test, the air cuffs are placed at the middle phalange of your testing fingers and strain gauges placed at your nail base to track the changes of finger volume. This is a non-invasive method used to monitor the finger circulation and you can find more information about plethysmograph at https://www.healthline.com/health/plethysmography.

Are there any benefits in my taking part?

By taking part you will help to expand knowledge regarding how different active forces affect the dynamic interaction of the vibrating tools with users and find out the suitable hand forces exerted on the hand-held vibratory tools to minimise the negative impact on users.

Are there any risks involved?

There are some minimal risks including discomfort in the hand and arm induced by vibration exposure. The vibration and force will be monitored throughout the experiment by the experimenter to make sure the accuracy of testing stimuli. Vibration magnitude and duration used in this study are designed in accordance with the Institute of Sound and Vibration Research (ISVR) report on noise and vibration and the daily exposure limit set by Health and Safety Executive (HSE). If you are not comfortable with the vibration exposure, you can stop the testing at any time by removing your hand from the handle.

What data will be collected?

As part of this study, your email address, questionnaire and a signed consent form will be collected; the consent form will be digitised and the hard copy version shredded. These are personal to you

and will be kept securely on a University of Southampton, password-protected desktop that only the project supervisor can access.

Other than that, measurements will be taken during the session as described in the section What will happen to me if I take part? above. Although personal to you, it will not be possible to identify you from these measurements. The measurements will only be used for the purpose of this study.

All data will be kept for future research.

Will my participation be confidential?

Your participation and the information we collect about you during the course of the research will be kept strictly confidential.

Only members of the research team and responsible members of the University of Southampton may be given access to data about you for monitoring purposes and/or to carry out an audit of the study to ensure that the research is complying with applicable regulations. Individuals from regulatory authorities (people who check that we are carrying out the study correctly) may require access to your data. All of these people have a duty to keep your information, as a research participant, strictly confidential.

Do I have to take part?

No, it is entirely up to you to decide whether or not to take part. If you decide you want to take part, you will need to sign a consent form to show you have agreed to take part.

If at any time you decide you do not wish to continue, please just let the researcher know.

What happens if I change my mind?

You have the right to change your mind and withdraw at any time without giving a reason and without your participant rights being affected.

Your participation is voluntary and you may withdraw consent at any time without your legal rights being affected and without the need for justification.

If you withdraw from the study, we will keep the information about you that we have already obtained for the purposes of achieving the objectives of the study only.

What will happen to the results of the research?

Your personal details will remain strictly confidential. Research findings made available in any reports or publications will not include information that can directly identify you without your specific consent.

The results of this study will be reported in my dissertation and published solely within the University of Southampton. Results will typically be aggregated across all participants; no single participant will be identified.

Where can I get more information?

Should you require any additional information, please contact either the investigator (e-mail: S.Gao@soton.ac.uk) or the project supervisor (e-mail: y.ye@soton.ac.uk).

What happens if there is a problem?

If you have a concern about any aspect of this study, you should speak to the researchers who will do their best to answer your questions.

If you remain unhappy or have a complaint about any aspect of this study, please contact the University of Southampton Research Integrity and Governance Manager (023 8059 5058, rgoinfo@soton.ac.uk).

Data Protection Privacy Notice

The University of Southampton conducts research to the highest standards of research integrity. As a publicly-funded organisation, the University has to ensure that it is in the public interest when we use personally-identifiable information about people who have agreed to take part in research. This means that when you agree to take part in a research study, we will use information about you in the ways needed, and for the purposes specified, to conduct and complete the research project. Under data protection law, 'Personal data' means any information that relates to and is capable of identifying a living individual. The University's data protection policy governing the use of personal data by the University can be found on its website

(https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page).

This Participant Information Sheet tells you what data will be collected for this project and whether this includes any personal data. Please ask the research team if you have any questions or are unclear what data is being collected about you.

Our privacy notice for research participants provides more information on how the University of Southampton collects and uses your personal data when you take part in one of our research projects and can be found at

http://www.southampton.ac.uk/assets/sharepoint/intranet/ls/Public/Research%20and%20Integrity%20Privacy%20Notice/Privacy%20Notice%20for%20Research%20Participants.pdf

Any personal data we collect in this study will be used only for the purposes of carrying out our research and will be handled according to the University's policies in line with data protection law. If any personal data is used from which you can be identified directly, it will not be disclosed to anyone else without your consent unless the University of Southampton is required by law to disclose it.

Data protection law requires us to have a valid legal reason ('lawful basis') to process and use your Personal data. The lawful basis for processing personal information in this research study is for the performance of a task carried out in the public interest. Personal data collected for research will not be used for any other purpose.

For the purposes of data protection law, the University of Southampton is the 'Data Controller' for this study, which means that we are responsible for looking after your information and using it properly. The University of Southampton will keep identifiable information about you for until successful completion of my degree after the study has finished after which time any link between you and your information will be removed.

To safeguard your rights, we will use the minimum personal data necessary to achieve our research study objectives. Your data protection rights – such as to access, change, or transfer such information - may be limited, however, in order for the research output to be reliable and accurate. The University will not do anything with your personal data that you would not reasonably expect.

If you have any questions about how your personal data is used, or wish to exercise any of your rights, please consult the University's data protection webpage

(https://www.southampton.ac.uk/legalservices/what-we-do/data-protection-and-foi.page)

where you can make a request using our online form. If you need further assistance, please contact the University's Data Protection Officer (data.protection@soton.ac.uk).

Thank you.

Thank you for taking the time to read the information sheet and considering taking part in the research.

Appendix B Consent Form

Here, only the consent form to subjects in experiment 1 reported in Chapter 4, is provided as an example. Consent forms to be completed by subjects in follow-up experiments are similar.

Study title: Acute effects of force and vibration on finger blood flow and finger temperature

Researcher name: Shuxiang Gao

ERGO number: 55633

Participant Identification Number (if applicable*):*

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (2020-10-30/ V2 of the participant information sheet) and have had the opportunity to ask questions about the study.	
I agree to take part in this research project and agree for my data to be used for the purpose of this study.	
I understand my participation is voluntary and I may withdraw (at any time) for any reason without my participation rights being affected.	

Name of participant (print name) ……

Signature of participant……

Date……

Name of researcher (print name) ……

Signature of researcher ……

Date……

Appendix C Health questionnaire

Here, only the health questionnaire to subjects in experiment 1 reported in Chapter 4, is provided as an example. Health questionnaires to be completed by subjects in follow-up experiments are similar.

Study title: Acute effects of force and vibration on finger blood flow and finger temperature

ERGO number: 55633

Subject basic information:

Name			
Gender	F / M	Age(years)	
Stature(m)		Mass(kg)	
Hand size(cm)		Hand circumference(cm)	
E-mail			

Before completing this part, please read the 'Information for Subjects' on the reverse side of this sheet.

Do you smoke? (……Cigs per day)	• yes • no
Have you ever suffered from cold hands?	• yes • no
Do you have any of the conditions listed on the reverse side of this form?	• yes • no
Have you ever suffered an injury to your fingers, hands, arms, neck?	• yes • no
Are you under medical treatment or suffering disability affecting your daily life?	• yes • no

Information for Subjects

Persons with any of the following conditions are usually considered unfit for vibration experiments

Active disease of respiratory system: including recent history of coughing-up blood or chest pain.

Active disease of the gastro-intestinal tract: including internal or external hernia, peptic ulcer, recent gall-bladder disease, rectal prolapse, anal fissure, haemorrhoids or pilonidal sinus.

Active disease of the genito-urinary system: including kidney stones, urinary incontinence or retention or difficulty in micturition.

Active disease of the connective tissues: including rheumatoid arthritis, scleroderma, granulomatosis with polyangiitis, Churg-Strauss syndrome, lupus, microscopic polyangiitis, polymyositis or Marfan syndrome.

Active disease of the cardiovascular system: including hypertension requiring treatment, angina of effort, valvular disease of the heart, or haemophilia.

Active disease of the musculo-skeletal system: including degenerative or inflammatory disease of the spine, long bones, or major joints or a history of repeated injury with minor trauma.

Active or chronic disease or disorders of the nervous system: including eye and ear disorders and any disorder involving motor control, wasting of muscles, epilepsy or retinal detachment.

Pregnancy: any woman known to be pregnant should not participate as a subject in a vibration experiment.

Mental Health: subjects must be of sound mind and understanding and not suffering from any mental disorder that would raise doubt as to whether their consent to participate in the experiment was true and informed.

Recent trauma and surgical procedures: persons under medical supervision following surgery or traumatic lesions (e.g. fractures) should not participate in vibration experiments.

Prosthesis: persons with internal or external prosthetic devices normally should not participate in vibration experiments (although dentures need not exclude participation in experiments with low magnitudes of vibration).

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