Protecting Prosthetics: A Study into Vibrotactile Feedback as Urgent Signals for Upper-Limb Prostheses

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Declaration of own work

I declare that the work in this MSc dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

Finlo Heath

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This project fits within the scope of ethics pre-approval process, as reviewed by my supervisor Dr Ben Ward-Cherrier and approved by the faculty ethics committee as application 12723.

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Abstract

Upper-limb prostheses have seen a surge in research and media attention in the past decade. However, device users still report a lack of dexterity and high cognitive load during use. Training can help mitigate both of these issues, but in order to train in ways which mimic the use of the natural hand, the device should be used without visual confirmation. Given the high cost of actuated prostheses, it is essential that users should have robust safety alerts, just as the natural hand can deliver somatosensory information without being visually observed. Vibrotactile feedback provides a promising method which can substitute for natural urgent signals. This project develops hardware for able-bodied individuals to use a commercial EMG-actuated prosthetic and a vibrotactile delivery and measurement system to simulate urgent signals from this device. A user study with 27 participants (18 male, 9 female) investigated participant reaction time and perception to different vibration intensities under No load, Cognitive load & Physical load. Performance was similar for No load and Cognitive Load, but a statistically significant difference in reaction time ($P = 3.78 \times 10^{-20}$) **and perception across four of six intensity levels (see table 4.1), was found for the Physical load condition. For the original documentation, CAD files & anonymised experimental data, readers can view the author's GitHub.**

Contents

1 Introduction

The field of actuated prosthetics has seen a significant increase in research focus and subsequent advancement in the last two decades [1]. Developments in upper-limb prostheses have led to devices with multiple articulated grips, customisable appearances and, though still expensive, more competitive pricing for users [2], [3], [4]. Despite this, the disparity between modern devices and the natural hand is still large. Abandonment rates of these devices are high [5], [6], with some users opting for solely cosmetic devices instead of actuated or body-powered devices capable of performing tasks [7].

One aspect of the performance gap between natural and artificial hands is haptic feedback; particularly during dexterous manipulation or operation without visual confirmation. The natural human hand relays complex sensory feedback when touching or grasping an object, providing a person with texture and temperature information, as well as their own grip force [8]. This allows the person to discern the degree of contact with the object, such as whether they are securely holding it or not, with no requirement for visual confirmation. In contrast, while contact between a prosthetic hand and an object will provide some measure of torque on the residual limb [9], this does not equate to the fine-motor control required for confident use without visual confirmation [8][10]. This may be one contributing factor to the high abandonment rate of modern prosthetics, their current functionality does not restore enough dexterity to the user [11].

In this project, we introduce a fundamental level of haptic feedback for use in conjunction with upper-limb prosthetic devices. Specifically, we investigate the use of vibrotactile feedback to deliver *"urgent"* signals with the intention of immediately capturing the user's attention. Achieving fine dexterity in the application of upper limb prosthesis is dependent on dedicated user training to form new neural pathways [10], as well as on the number of configurations the prosthetic is capable of [11]. To more closely restore functionality comparable to the natural limb, users must be able to train operation of their device without visual confirmation. To enable this, the first consideration should be robust safety features for both the operator and their device, given the typically high cost of actuated prosthetics. Vibrotactile actuators are low cost with a small form factor which can be easily worn compared to other haptic modalities [12]. We assert that vibrotactile feedback is the most suitable method for delivering highly perceptible signals which encourage the user to return visual attention to the device; analogous to pain in the natural hand.

The prosthetic device used in this study is the Covvi hand [13]. This is a commercial device available for NHS patients requiring upper-limb prosthetics and uses a universal socket design. The myoelectric dual-electrode control method, 12 grip choices and force-sensitive resistors in each fingertip make it an excellent choice for this study and further haptic integration in the future.

Given the above discussion, the aims of this project are threefold:

(a) *To develop a platform that enables able-bodied participants to use the Covvi hand.*

(b) *To create a vibrotactile feedback system which can work in conjunction with the Covvi hand to simulate urgent signals and measure user response time.*

(c) *To discern the efficacy of vibrotactile feedback on the upper arm for use as urgent signals to protect expensive advanced prosthetics.*

Our objectives to achieve these aims are as follows:

1. Review key results found by *Alex Smith et al.* [14][15] in their evaluation of multi-channel feedback arrays in relation to digit discrimination. Assist Smith in their next study to gain first-hand experience with the current software and hardware being used, as well as experience running a user study.

2. Work with the Covvi Hand [2] to develop a platform for able-bodied individuals to use the hand as an extension of their right arm. This allows for able-bodied participants for the

user study as well as first-hand experience of the device when testing vibrotactile haptic implementations.

3. Develop a vibrotactile haptic feedback system.

4. Investigate ways of modulating vibrotactile signals and research alternative motor actuators with the aim of decoupling frequency and amplitude of vibration so that these can be varied independently. Decide upon what type of signal variation we will investigate in the user study.

5. Design and run a controlled user study with human participants to measure user perception of vibrotactile feedback when using the prosthetic under different cognitive load conditions.

6. Evaluate study results to determine the optimal implementation of vibrotactile haptic feedback as urgent signals to protect upper-limb prosthetics.

2 Literature Review

We can consider several key themes in the literature which should be explored in order to clarify the merit of this study. We begin with haptic feedback and continue on to outline the current state of upper-limb prosthetics, before looking closer at platforms for able-bodied users and the application of haptics in upper-limb prosthetics.

2.1 Haptic Feedback

Hayward V et al. [16] defines haptic interfaces as those which make use of touch and kinesthesia to facilitate communication between humans and machines. A notable and lasting advantage of haptic communication over other modalities (visual, audio) is that it can be delivered privately, alerting only the intended user. This makes it suitable to deliver sensitive information or as a way of avoiding disturbance to other people, such as passengers in a car, where only the driver requires information [17]. *Cipriani C et al.* [18] demonstrated experimentally, that users will integrate haptic feedback into their control method for using a robotic hand, meaning this feedback has a real influence on user behaviour. Further, many studies demonstrate the utility of haptic feedback. *Katzschmann R et al.* [19] utilised haptic feedback in conjunction with time-of-flight sensors to provide visually impaired users with an obstacle avoidance method that leaves their hands free for use, unlike a traditional white cane.

The optimal type and level of haptic feedback is highly dependent on context. *Wildenbeest J et al.* [20] investigated the effects of providing different levels of haptic feedback in teleoperation assembly tasks. They found that low-frequency haptic feedback provided significant overall improvements in minimising completion time and reversal rate (the number of steering corrections per task). However, more substantial haptic feedback, including a "full spectrum of haptic feedback" via direct-controlled equivalent, provided only marginal gains in overall task performance. This indicates that, for some applications, additional haptic feedback beyond low-level simple feedback may have depreciating performance improvements. However, for fine-dexterity motor tasks, *Koehn J K et al* [21] found a strong preference for the inclusion of haptic feedback in minimally invasive surgery; converting end-effector-mounted accelerometer readings to vibrations actuated by voice coil actuators mounted to the surgeon's control handles. This provides real-time, modality-matched haptic feedback. However, they did not conflate this preference with the surgeon's performance with or without haptic feedback. This same method was re-contextualised for telerobotic construction by *Gong Y et al.*, who confirmed the finding that users preferred the addition of haptic feedback and further found that this feedback enabled user's to *"create smaller tool vibrations and exert smaller forces on the construction materials"* - essentially an improvement in their task performance.

2.1.1 Vibrotactile Feedback

In the above studies, vibrotactile feedback is utilised to provide moment-to-moment feedback. This is relatively rare given that users report continuous vibrotactile feedback as more unpleasant than other modalities such as skin squeeze or shear [22]. For this reason, many studies have turned to the principle of Discrete Event-driven Sensory feedback Control (DESC) in their implementation [14][18][19][23]. Feedback is delivered in individual bursts every time a state changes in the sensor. The user is notified only of changes, receiving no feedback while the current state persists. This has the key benefit of reducing user desensitisation to the vibrations, improving their perception of each signal. This was used to great effect by *Mulder S et al.* [24] who integrated vibrotactile feedback with a simple force-sensitive resistor on the heel of volleyball players. Vibrations were provided whenever players' heels contacted the floor, reminding them to stay in a more active position on the balls of their feet.

Regardless of implementation, vibrotactile feedback is widely used in academia as the most convenient and cost-effective form of haptic feedback [12][25]. Commercially, it is ubiquitous for delivering "silent" notifications to smartphones and watches. Though it has limitations in terms of sensory substitution, clever use of placement, signal characteristics and, in particular, training can far outweigh any lack of intuitiveness this modality struggles with [15][26][27].

Given its strength in perceptibility and superior utility for discrete signalling, vibrotactile feedback is well suited as a substitution for pain or other urgent signals; those which are not used moment-to-moment, but must not be missed when they are sent. The issue of participants finding vibrotactile signals to be unpleasant should be addressed, as users may abandon devices they regard as unpleasant to use. It may be that we can elicit the same level of perception at a significantly lower vibration intensity, decreasing discomfort for users. This is investigated as part of the project. One can also consider to what extent haptic feedback distracts from the user's current activity. In this study, this will be accounted for by measuring performance in the tasks along with perception and discrimination of the feedback signal.

Properties of Vibrotactile Feedback

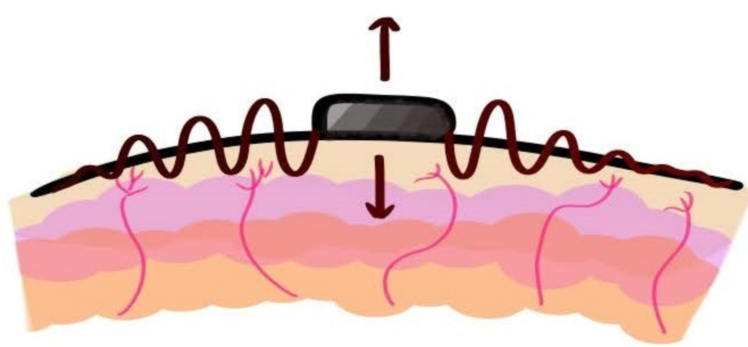


Figure 2.1: A grey button vibrotactile motor oscillates perpendicular to the plane of the skin, creating transverse waves (dark red) which dissipate as they propagate away from the motor. Vibration propagation is affected by different layers of skin, tissue and bone.

The properties of vibrational motors can be articulated using frequency and amplitude. The frequency is the rate of motor oscillation, the amplitude is the maximum displacement from equilibrium which the motor moves during each oscillation [28]. Intuitively, vibrotactile motors create transverse waves which propagate through the skin of the user, as illustrated in Figure 2.1. Research by *Azadi M et al.*[29] shows that the vibration of actuators is clearly affected by the local composition of the skin. For example, if the actuator is placed on the skin near underlying bone, such as the anterior tibialis (front of the shin), vibration amplitude is considerably dampened in comparison to placement on the posterior tibialis [30]. Further, if using a vibrational band, the tightness of the band also affects vibration amplitude. For this reason, this project took care to place the vibrational band in the same position on each participant and with the band tightness in the same range. Further details are given in Section 3.3.

Human perception of vibration can also vary with cognitive and physical load. *Yoshida T et al.* [31] observed a significant increase in participant reaction time to vibrations when either a cognitive or physical load was introduced. The cognitive load also resulted in an increase in vibration perception threshold. One should also consider Weber's Law, first formulated by *Gustav Theodor Fechner* [32]. The law states that the "just noticeable difference", δx, between two stimuli is directly proportional to the magnitude, x, of the initial stimuli. This can be written as:

$$\delta x = Kx$$

Where K is a constant. As discussed in subsequent sections, the operation of actuated myoelectric prosthetics places a significant cognitive burden on the user, so the potential decrease in user perceptivity and responsiveness to vibrations while using a prosthetic device forms the focus of our study. Whether Weber's law proves true in this context is also investigated.

2.2 Upper Limb Prosthetics

Research into upper-limb prosthetics has in recent years seen a shift in focus from trying to deliver purely functional devices, to additionally capturing the form of the natural hand to make the device more aesthetically pleasing [33]. Modern devices are capable of multiple articulated grips, contain multiple sensors and often have customisable visual styles [2][3][4], but these come with the caveat of a considerable price tag whether borne by the user or their local healthcare services [34]. Some devices aim to provide an affordable solution for users without access to considerable wealth [35], which can provide considerable functionality, often in exchange for losing the mimicry of the natural hand. These devices aim to allow users to successfully carry out Activities of Daily Living (ADLs) as defined by the NHS [36]. While this aim is achieved using many of these devices, they are not always utilised in the intended way. For example, *Spiers A et al.* [37] observed eight upper-limb prosthesis users operating their devices outside of lab conditions. They found that the majority of actions performed using the prosthetic were non-prehensile, 60% & 79% for myoelectric and body-powered devices respectively. Prehensile actions specifically involve grasping, whereas non-prehensile are less dexterous pushing or clamping movements. Comparatively, only 16-19% of natural hand activity was non-prehensile. Two conclusions can be drawn from this study. Firstly, the disparity in prehensile actions between prosthetics and natural limbs indicates that these devices are still a long way from replicating natural dexterity. Secondly, whilst the previous supposition holds, these devices should be designed with the assumption that they will be used primarily for non-prehensile actions; there may be more utility in simplifying these devices as opposed to providing many different articulated grasping patterns. However, despite the current limitations, strides are being made in prosthesis technology which will continue to close the functionality gap to that of the natural hand. Reviewed by *Marinelli A et al.* [33], neuroprosthetics in particular show promise in allowing intuitive control over artificial limbs, with the drawback of being both costly and invasive.

2.2.1 Attention & Operation Without Visual Confirmation

One of the key limitations preventing prosthesis users from using their devices in the same manner as a natural hand is the lack of haptic feedback - an essential component of fine dexterous motor control. The natural hand can sense a range of feedback via shallow and deep mechanoreceptors in the skin and recruits this for dexterous tasks [38]. A 2016 review of the needs of upper limb prosthetic users [11] found that 98% of users desire a feeling of grasping force and temperature; fundamentally a request for haptic feedback integration in their devices. This review found tactile sensation integration was second in desirability only to having greater manipulation and grasping abilities - an improvement that will itself be realised through haptic feedback integration in control mechanisms [18][38][39].

Due to proprioception, humans can operate their biological limbs for many tasks without visual confirmation (without looking) or indeed conscious thought [40]. To move toward this ability for prosthesis users, researchers must consider the cognitive load on users required to operate their devices as well as how to provide sensory information about the device when the user is not looking at it. Operation of current actuated prosthetics can require a large cognitive load due to reductive control strategies being used to activate multiple grip types in the hand [11][41]. Dedicated training contributes to a reduction in abandonment rate [42] and improved user performance [43], but the literature is inconclusive on whether this is due to a reduction in cognitive load during operation. Ultimately, the use of appropriate haptic feedback can help lessen the cognitive load on users [44] as well as offer a method of informed operation without visual confirmation.

To maximise user operation without visual confirmation, the highest possible haptic signal clarity must be achieved, so that users can rely on their assessment of haptic feedback during operation. *Antfolk C et al.* [45] demonstrated that pressure stimulation outperforms vibrotactile stimulation in user discrimination of stimulation location. This is expected given the shallow mechanoreceptors responsible for pressure detection have a much finer field of influence compared to the deep mechanoreceptors detecting vibrations, in addition to the propagation of vibrations through the skin. Further, this study found that accounting for a user's "phantom map" - the phenomena some amputees experience of having phantom sensation corresponding to each digit of the lost hand at specific points of the residual limb - can further improve the localisation of haptic stimuli. This study indicates the use of pressure sensation as optimal for improving the dexterous operation of prosthetics.

2.2.2 Sensory Substitution

This phenomenon is the use of one sensation to provide information about another sensation of a different type or position. For example, the use of vibration on the skin to indicate the closing or opening of the digits of a robotic hand [15]. In the case of prosthetics, some measure of sensory substitution is inherently unavoidable; information from the prosthetic digits must be conveyed to the user by some mechanism other than identical sensation.

Another major application for sensory substitution is indicating pain or damage to a robot. Triggering Nociception - pain reception in the human body - is not ethically viable, yet pain responses often indicate important stimuli. In teleoperation, it is not appropriate for the operator to feel pain if the robot is damaged, but substituting this feedback means the user is still aware of it. *Sobhani M et al.* [46] have pioneered work on immersive virtual reality in conjunction with teleoperation of a robot, with the application of more intuitive operation of nuclear decommissioning robots.

Haptic feedback, such as vibrations of increasing amplitude, could be used to inform the operator that the robot is taking radiation damage, without requiring a visual interruption which could cause operator mistakes.

Two main components must be considered when describing sensory substitution, modality and location. Modality describes the type of sensation. Research indicates that modality-matching, the use of the same type of sensation as the one the system is attempting to convey, can provide better user discrimination [45]. Specifically, the use of pressure stimulation was demonstrated to outperform vibrotactile stimulation in the discrimination of which digit of a robotic hand had pressure applied to it. While this may suggest that mechanotactile actuators are the superior choice, as pointed out by *Smith et al.* [14], vibrotactile sensors have the advantage of being more compact and requiring less power contributing to their widespread use in practical haptics research [47].

The complexity of the sensation being substituted may also impact the best choice of haptic feedback. *Smith et al.* [15] uses five vibrotactile motors to investigate the optimal array morphology for conveying haptic feedback for each digit of a robotic hand. Study Participants made errors in discriminating between the active motors partly due to the nature of vibrations as waves propagating through the skin. Constructive and destructive interference will affect vibration amplitude at different positions on the skin [48]. Additionally, as outlined in section 2.1.1, placement on the body and band tightness further affect vibration propagation. For this reason, complex tactile sensation combinations may be better simulated with other modalities.

2.2.3 Haptic Feedback For Prosthetics

Integrating haptic feedback with upper-limb prosthetic offers the potential of recovering fine dexterity that artificial limbs have yet to achieve. additional components however will increase the weight of the prosthetic and reduce battery life; the haptic system would need to draw power from the prosthetic battery to maintain portability. Therefore any haptic integration must be carefully optimised. Vibrotactile motors are an excellent choice for economic additional weight, power consumption and lifetime. While the industry standard is 1×10^5 cycles of active and passive at a frequency of 1Hz ($\approx$ 28 hours of active operation), retail motors can outperform this by some margin [49]. In the context of urgent signals, we can estimate that with average daily use of ≤ 50 essential vibrotactile alerts, the system would operate for a minimum of 5 years before replacement motors are required. For DC ERM motors, as used in this study, the relationship between voltage, current draw and resultant amplitude is directly proportional, meaning that the power taken from the battery is dependent on vibration intensity [50]. For these motors, current draw, I, ranges from $12A$ at minimum vibration intensity to $85A$ at maximum vibration intensity. The Covvi hand prosthetic used has a battery capacity rated at $2600mAh$ [51]. A single motor operating at maximum intensity could therefore be powered continuously for $t = \frac{2600}{85} = 31$ hours $(2s.f)$. The array of four parallel motors used in this study could then be powered for $\frac{t}{4} = 7.8$ hours. In the context of urgent signals delivered using DESC in infrequent short pulses and not always at maximum intensity, we can surmise that the power draw of the vibration motors is negligible compared to that of the actual prosthetic.

Haptic feedback integrated with prosthetic devices must utilise the sensory data from the device. For the purpose of urgent signals designed to prevent damage, the most useful would be force sensitive resistors (FSRs), thermistors and a moisture sensor. FSRs, commonly embedded in the fingertips of prosthetic devices, can be used to sense whether the device is being crushed. Thermistors would indicate whether the hand is overheating, for example if the user rests it near to an open flame. A moisture sensor would inform the user in the case that the device were splashed with a liquid. In each case, spikes in the sensor readings could stimulate a simple vibration signal. The key requirement would be to draw user attention to the device, therefore a bespoke signal for each sensor is not required. Use of compound sensors such as the Biotac [52], an artificial fingertip with multimodal pressure, vibration and temperature sensitivity, could help to achieve the required sensitivities in prosthetic devices.

Regarding current research into sensory feedback mechanisms for upper-limb prostheses, *Sensinger J & Dosen S* [10] provide a review. The majority of studies look at mechanisms for continuous closed loop control, commonly using electrotactile or vibrotactile feedback to provide information on hand configuration or grip pressure. However, stimuli sources such as EMG (Electromyography) or FSR data can be particularly noisy, making it difficult to provide haptics which are robust to both false positives and false negatives. *Chaubey P et al.* [53] found that upper limb prosthetic users became fully desensitised to continuous vibrotactile feedback after 66 seconds on average. This supports the use of DESC (section 2.1.1) as a superior delivery mechanism for urgent signals which users must not become desensitised to. While descrete signals will also consume less power, as calculated above, this difference is likely to have a negligible impact on overall battery life of the prosthetic. Despite an abundance of research into haptic implementation for upper-limb prosthesis, none of the major commercial devices have yet integrated any form of active haptic feedback for users.

Combined Modality Haptic Feedback

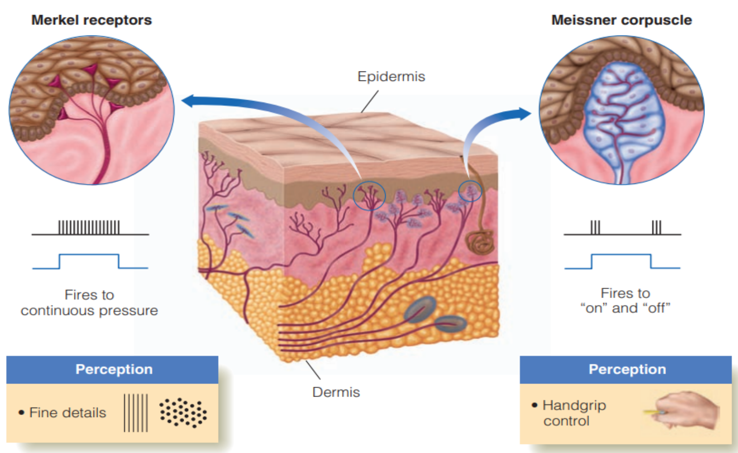


Figure 2.2: A cross-section of human skin showing the shallow mechanoreceptors for continuous and transient contact [54]. Deep mechanoreceptors (which can sense vibrations) are visible as blue pods in the dermis layer.

The above research indicates that a combination of vibrotactile and pressure or skin stretch feedback may be ideal to maximise user comfort without sacrificing their perception of urgent signals. This could be realised by combining rigid vibrotactile actuators with soft-robotic fluid based actuators.

The future solution to maximise real-world utility would reserve vibrotactile feedback for urgent alerts, making use of more pleasant soft-actuated squeezing or pinching for moment-to-moment feedback. Different sensations are conveyed by stimulating different aspects of the human somatosensory system, multimodal haptics allow an exponential increase in deliverable sensations due to submodality convergence; the phenomenon of different combinations of stimulated tactile receptors producing different sensations such as texture, vibration and shape [55]. Indeed, to achieve fine dexterity in teleoperation or prosthetics, users must be provided feedback which stimulates both shallow and deep, sustained and transient contact mechanoreceptors [38]. These are displayed in Figure 2.2.

The combination of compression, shear and vibrotactile feedback has been explored by *Zhu M et al.* with the PneuSleeve device [56]. The researchers suggest applications such as notifications, navigation prompts and remote social touch using this device. For sensations increasing in importance, one could envision a sensory phase from soft-squeeze to hard-squeeze to vibration as the importance of acquiring the user's attention increases. Vibrations are generated by stimulating all the soft actuators at once and are reported as differing in sensation to vibrations from a rigid motor.

While multimodal haptics certainly constitutes a key area of future research, current systems are too bulky to be truly functional for portable technologies.

2.3 Prosthetic Platforms for Able-Bodied Users

The motivation for creating a platform (or simulator) which allows able-bodied individuals to user upper-limb prosthetics is primarily to vastly increase the number of potential participants for user studies involving use of prostheses, reducing the burden on those with limb differences to participate in large numbers of studies. In addition, these platforms allow prosthesis engineers to test their own changes, allowing them to be a part of their own user-centred design process. *Sinke M et al.* [57] provide an excellent review of the current upper-limb prosthesis simulators. From 52 papers, 32 simulator designs were identified as using three recurring prosthetic placements: dorsal (above the natural hand), palmer (below the natural hand) & axial (extending out from the natural hand). These are displayed in Figure 2.3. Axial placement is chosen in 75% of simulators, given the device is in the same line of action as the natural hand. However, dorsal or palmar placement benefits from lower torque on the arm of the user by moving the device centre of mass closer to that of the natural arm. Device position is the key difference between simulators and genuine prosthetic use. Another important consideration is that participants with intact limbs typically have greater muscle development than the affected limb of those with limb differences. For EMG control, this could affect performance and thus generalisability of study results. For body powered simulators, it is less likely to be significant. Simulators can indicate device performance but do not provide information on device comfort for target users. Overall the advantage of increased participant numbers is considered to outweigh disparities between simulator and real prosthetic use.

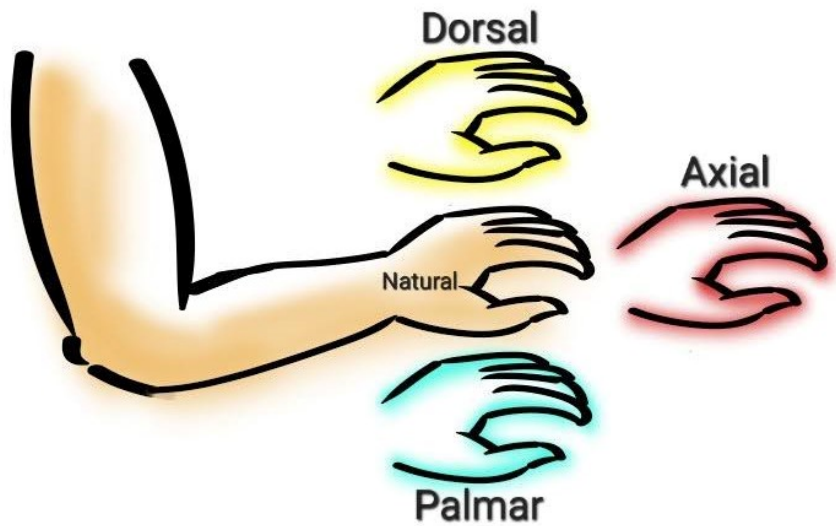


Figure 2.3: The three standard positions for prosthetic device placement using simulators, as identified by *Sinke M et al.* [57].

2.4 Wider Applications

In addition to prosthetics, improvements in haptic technologies are being driven by consumer demand for more immersive virtual and augmented reality experiences, as well as the desire for more dexterous teleoperation of robots. Multimodal haptic technology is the key to the development of both fields as the solution for stimulating multiple aspects of the human somatosensory system [55]. As mentioned in section 2.1], haptic feedback has utility for individuals with disabilities other than limb differences, such as navigation prompts for the visually impaired [19]. Haptic feedback improves dexterity in teleoperation tasks [20], [58], which has major applications for safety-critical tasks such as nuclear decommissioning using combined virtual reality and teleoperation [46]. In each of these applications, the use of vibrotactile feedback to convey urgent signals may be considered. For safety-critical tasks, the controlled phased feedback from soft-actuated squeeze to vibration, as suggested in section 2.2.3, would be appropriate.

2.5 Summary

While there are many interesting avenues being explored in haptic feedback today, achieving fine dexterity in the application of upper limb prosthesis remains dependant on dedicated user training to form new neural pathways [10], as well as on the number of configurations the prosthetic is capable of [11]. Until haptic-enabled prosthetic systems reach feedback levels comparable to the natural hand, its impact will be more significant if it is used discretely to draw user attention to the prosthetic itself. Haptics, particularly vibrotactile stimulation, is perfectly suited to quickly acquire the user's attention. Once the user is focused on the prosthetic, further haptic feedback provides a less significant contribution to their ability to manipulate it relative to the level of training the user has had with the device [8].

However, to allow users to confidently train to operate their prosthetic device without visual confirmation, the first consideration should be robust safety features for both the operator and their device, given the typically high cost of actuated prosthetics [11]. For this, users require clear, highly perceptible signals that are unlikely to be missed, even if the user is under cognitive load. Based on the literature discussed in the section 2.1.1, vibrotactile feedback is best suited for this requirement, delivering highly perceptible signals which encourage the user to return visual attention to the device. Once the user can rely upon receiving this feedback when necessary, they will feel less pressure to check on the device during proprioceptive operation. This will improve the quality of their training and thus their ability to operate the device without visual confirmation.

Hence, we propose the use of discrete vibrotactile feedback in upper limb prosthetics as the delivery mechanism for urgent feedback, such as damage to the hand - effectively a substitute for pain. In addition to the high cognitive load of controlling actuated prosthetics [11], users must be able to carry out tasks day-to-day which will require varying levels of attention. The question of how to maximise the user perception and discrimination of these urgent signals while under cognitive load will be investigated by the user study undertaken in this project.

3 Research Methodology

Now that we have established a motivation for the integration of urgent vibrotactile signals with prosthetic devices, we consider how to test for the optimal implementation configuration. There are many factors one can investigate, vibrotactile signals alone can be varied by frequency, amplitude, signal pattern as well as actuator placement on the skin. In this study, we control for constant actuator band position, tightness and signal pattern. The frequency and amplitude are co-varied as a single "intensity" measurement, detailed in section 3.3. Below, the hypothesis, and independent and dependent variables are stated. Following this, separate sections are given for the hardware development of the prosthetic platform and haptic band. Finally, the user study design is given. The exact steps taken with participants in each trial are also provided in appendix A.1.

3.1 Hypothesis & Independent and Dependent Variables

Given the discussion in section 2.5, our study hypothesis is stated as follows:

The reaction time and perceptivity of users to vibrotactile feedback will be negatively impacted by cognitive and physical load. Further, these variables will also be affected by the applied intensity of the vibration, where more intense vibrations will be required during cognitive or physical load to achieve the same reaction time and perceptivity as without load.

If this hypothesis proves to be valid, we can then propose a method by which to optimise the vibration intensity of urgent signals based on the signal stimuli as well as the sensor readings and motor activity in the hand; a more active prosthetic is an indicator of physical load, thus a more intense signal should be delivered to the user. If sensor and motor activity in the prosthetic is low we can deliver signals of a lower intensity, making the assumption that the user is not under load. This both helps to conserve battery life and improve user experience by avoiding unnecessarily jarring signals, which users may consider unpleasant. Unfortunately, no data acquired by the prosthetic can provide a meaningful interpretation of the user's cognitive load; a shortcoming of this feedback optimisation solution.

In each condition, our dependent variables (DVs) are therefore:

1. User reaction time to vibrotactile feedback
2. User perception of the intensity of vibrotactile feedback

Our single independent variable (IV) during each condition is:

1. Applied vibrotactile intensity

Additionally, there will be three conditions in which the IV will be varied and the DVs measured:

1. No additional load
2. Cognitive load
3. Physical load

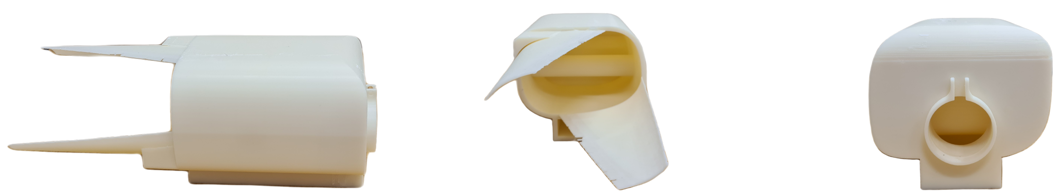
Following the experiment, statistical analysis will be used to compare user performance across conditions and intensities, to determine the potential merit of a controlled variable vibrotactile signal intensity based on the activity level of the prosthetic motors and sensors.

3.2 Developing a Platform for Able-Bodied Users

Section 2.3 showed that, while multiple designs have been made which allow able-bodied users to control and use prosthetic devices, there are changes which could be made in order to provide new benefits. In particular, added functionality in the form of same-arm EMG control could be acquired at the cost of EMG reading clarity. The key benefit of same-arm EMG control is that it mimics how the device would naturally be used by someone with a limb difference and allows for two-handed tasks, performed cooperatively between the natural hand and prosthetic. The difficulty this causes is that the lifting weight of the prosthetic ($0.57kg$ [13]) activates the extensor carpi radialis longus muscle along which the “hand-opening” EMG is placed. This creates an *always on* signal which can make it difficult to close the prosthetic with the antagonistic muscle.

To manage this trade-off, the platform went through three major design iterations. The platform was designed to fit a right-hand EMG-actuated prosthetic and is worn on the user’s natural right arm.

The first iteration used a closed design with an internal handle, seen in Figure 3.1. It has two wings which taper in thickness as they run along the forearm. The prosthetic wrist locking mechanism is designed to fit a universal prosthetic Electric Quick Disconnect socket. The closed design was chosen as it would prevent users from attempting to use their natural hand and indeed it was thought that removing sight of the natural hand may encourage users to think of the prosthetic as the natural end to their right arm.



(a) Side view (b) Back view (c) Front view

Figure 3.1: The first iteration of the prosthetic platform for able-bodied users.

This design contained several major flaws, however. The closed box was too small for users with large hands, preventing them from properly gripping the handle. The tapered wings were intended to be flexible, such that they could be strapped onto the forearm, distributing the weight of the device further up the arm. However, the 3D print material used (ABS) has very little flexibility compared to PLA, which becomes more flexible with thinner printing. The wings were very stiff and so could not conform to the forearm.

Iteration two, shown in Figure 3.2, opened the top of the platform while maintaining the handle for a design that acted as an extension in line with the natural arm. It was thought that this may give improved dexterity, compared to having the prosthetic beneath or above the natural hand. The wings are removed and replaced with a single extended plate which prevents downward rotation by bracing against the bottom of the forearm. This design allowed for accurate manipulation with single EMG control (extensor carpi radialis longus) on the same arm or dual-EMG control using the un-loaded arm. However, the protracted position of the heavy prosthetic hand caused considerable strain on the arm, making it unsuitable for use over extended durations.

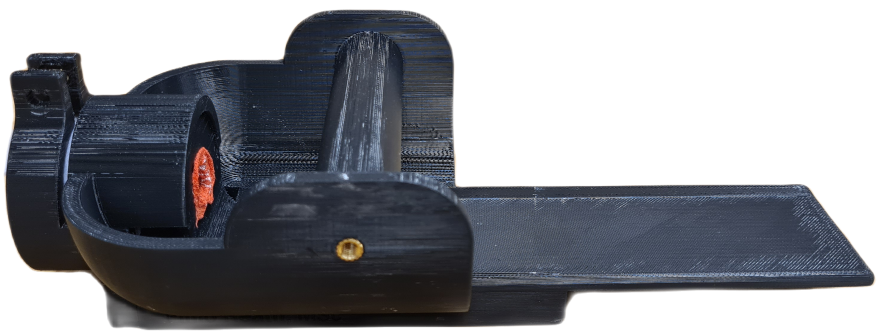


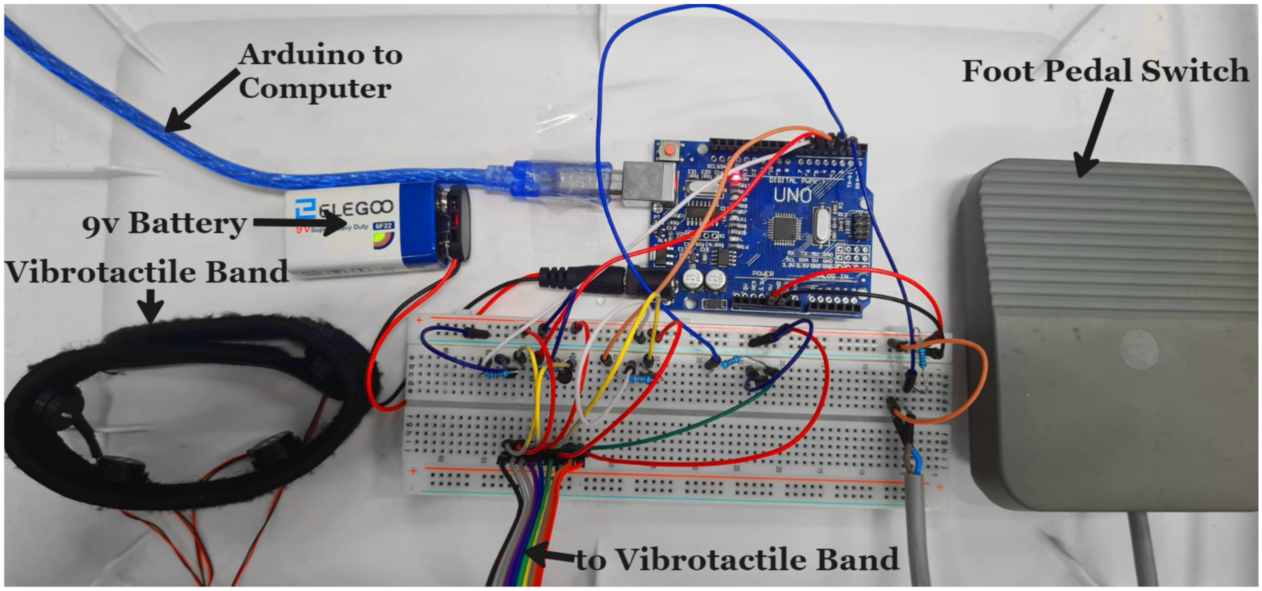
Figure 3.2: The second iteration of the prosthetic platform for able-bodied users. The design is open-top and reduced in size but still elicits high strain on the muscles.

The final iteration, Figure 3.3, revised the position of the prosthetic on the arm, allowing for dual EMG control on the same arm. The prosthetic sits below the natural hand, reducing torque on the user [9], compared to having it extend from the arm. Wide straps allow for superior weight distribution and free the wrist and hand to perform extension and contraction movements. The design also includes fitted slots for the battery pack and control panel, resulting in a sleeker end device. The same bolt-locking mechanism was maintained but thickened to increase strength. Same-arm dual EMG control allows the user to perform two-handed tasks which generalise well to performing ADLs. This design provides relatively responsive control for most users, though a myriad of physiological factors affect EMG signal quality and thus prosthetic responsiveness considerably [59].

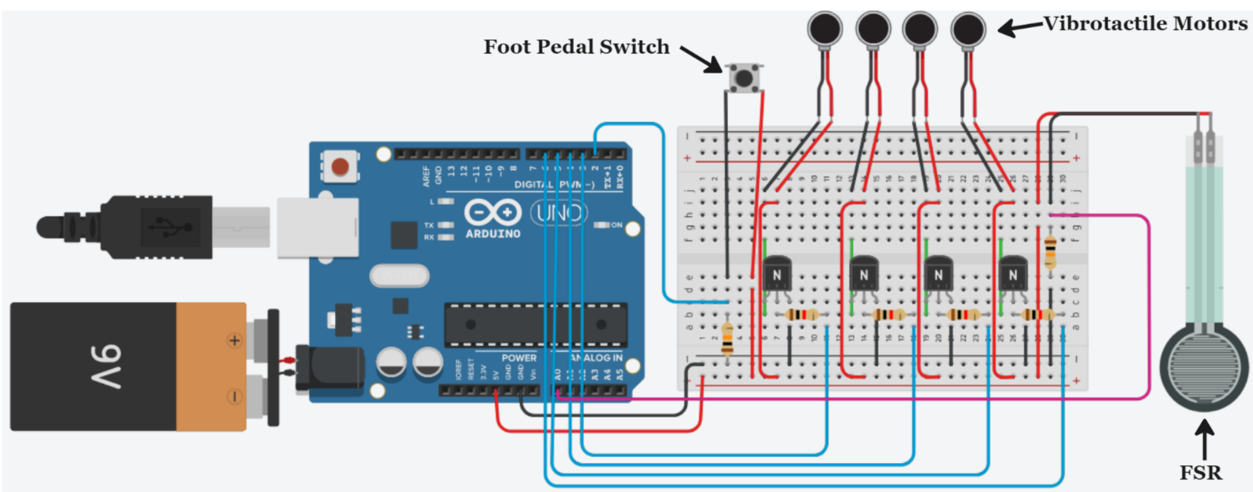
Figure 3.3: The final iteration of the prosthetic platform for able-bodied users. It is more ergonomic and designed to incorporate the prosthetic control panel and battery pack. It allows for same-arm dual EMG control providing an intuitive control method during two-handed tasks.

3.3 Developing Vibrotactile Haptic Circuitry

Given the expense of the Covvi hand, delivering real emergency alerts during the study was out of the question. Further, this commercial prosthetic has both closed hardware and software, meaning there is no established safe method of integrating additional hardware. Therefore a separate circuit was developed to deliver vibrations to the user simulating urgent signals. Controlled by an Arduino Uno, this circuit connected a vibrational array armband containing a force-sensitive resistor (FSR), to a binary (active/inactive) foot pedal. Since the user is aware that the signals are not real emergency alerts relating to the sensor readings in the prosthetic, this is not considered Wizard of Oz study design. The foot pedal is used to record reaction time whenever the user feels a vibration from the armband. This design choice was made as the user performs a two-handed task during the study, so the use of the foot for reaction time is appropriate. The Arduino circuitry is shown in Figure 3.4, the two code files for calibration and running the experiment conditions can be found in appendix A.3. PuTTY is used to output reaction times and signal intensities to a `.csv` file for data processing.



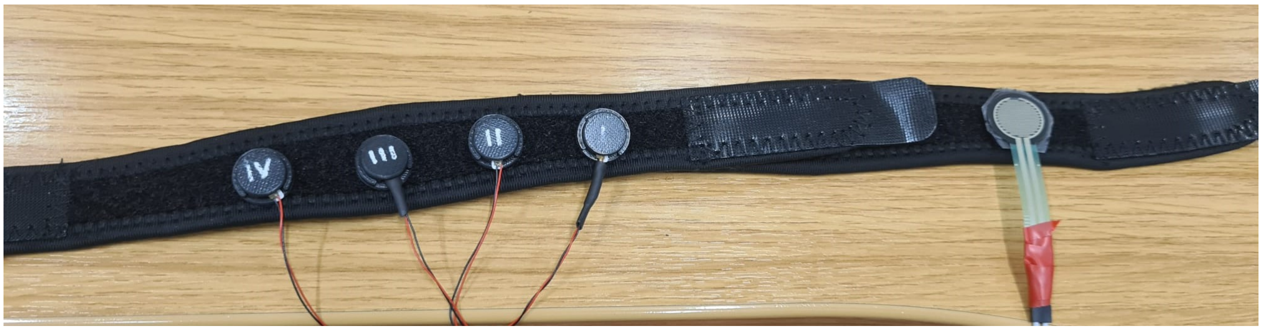
(a) Arduino Circuitry (Pictured)



(b) Arduino Circuitry (Diagram)

Figure 3.4: The circuitry connecting the vibrotactile band, FSR to measure tightness and foot pedal switch for reaction time. (a) shows the actual pictured circuitry, while (b) displays a diagram for additional clarity.

(a) Band Bicep Placement Marker



(b) Band Interior (in contact with skin)

Figure 3.5: The vibrotactile band is placed on the user's upper arm. It contains an array of 4 DC ERM motors, powered in parallel. The red bicep marker (a) is placed on the head of the user's bicep for consistent placement. The green FSR (b) allows for rough consistency in band tightness.

The vibrational armband contains four button vibrational motors which directly contact the skin. The band is marked to show which point should be placed on the bicep (Figure 3.5) and the FSR allows for a rough measurement of applied pressure when the band is in place. This allows us to ensure that the band is always applied in the same place and with tightness in the same small range for each participant. Achieving exactly the same FSR reading for each participant is unfeasible, as they are considered blunt instruments when it comes to measuring force or pressure.

Section 2.1.1 described vibrational waves in terms of amplitude and frequency. However, using an Arduino to control vibrational motors, one must use analogue pulse width modulation (PWM) to control the vibration. PWM ranges from 0 (always off) to 255 (always on) for a given time interval. While an increase in PWM correlates with an increase in vibration amplitude - shown in Figure 3.6 - this cannot be expressed as an exact function.

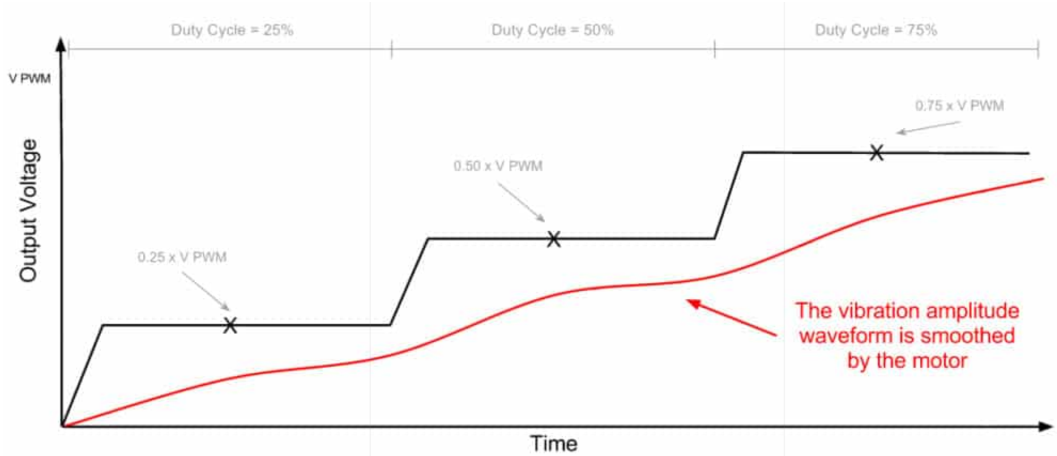


Figure 3.6: The output voltage to the motor increases in linear steps as the percentage PWM is increased, this results in a greater vibration amplitude [60].

Further, the amplitude and frequency of the ERM vibrational motors used could not be varied independently. For this reason, in our study, we consider vibration “intensity” as a percentage of PWM out of 255. A PWM value of 255 is considered 100% intensity producible by the motors. Intensity is no longer a fundamental variable as amplitude and frequency are, but a combination of varying the two together by changing PWM values. The use of Linear Resonant Actuator (LRA) motors was investigated. These motors operated at a (relatively) fixed resonant frequency and thus changes in amplitude can be applied independently [61]. However, these require the additional purchase of a driver to run with an Arduino given they operate with AC rather than DC. Their purchase and integration with the circuit ultimately fell beyond the financial and timing limitations of this project.

Following preliminary testing, the general threshold for perceptive vibrations was found to be 60 PWM (24% intensity). From this, we chose to use a range of regularly spaced PWM values increasing to 100%. The resultant intensity levels are shown in table 3.1

Intensity Level	Percentage (%)	PWM
1	24	60
2	38	99
3	54	138
4	69	177
5	84	216
6	100	255

Table 3.1: Six evenly spaced intensities are used, each increasing level corresponds to an increase of 39 PWM, or 15.5% intensity. Percentages in the table are rounded to the nearest integer.

3.4 User Study

Following the completion of the two hardware components, the design of the user study could commence. Through several iterations tested in preliminary trials, the below design and data collection methods were confirmed.

3.4.1 Design

This subsection contains the arguments for each of the design choices, the exact step-by-step procedure is given in appendix A.1, along with all of the participant facing documentation and the questionnaire. Once the user has consented to the study, they are fitted with two hardware components. The vibrotactile band is placed on the upper arm. The Electrode band for the prosthetic is placed on the lower arm just before the elbow, and the able-bodied prosthetic platform is strapped in place between the electrode band and the wrist. As outlined in section 3.2, the quality of EMG signals varies across users depending on band placement as well as physiological factors. The weight of the prosthetic activates the extensor carpi radialis longus, causing conflicting signals when some users attempt to close the prosthetic hand using the flexor carpi radialis; both muscles show activation at the same time so the prosthetic does not move. In the case that the prosthetic is too unresponsive, the control method is switched to single EMG alternating using only the extensor carpi radialis longus. This typically provides more responsive though less intuitive control of the prosthetic, the control method was recorded for each participant.

Following hardware fitting, the researcher confirms that the vibrotactile band is in the correct tightness range. This corresponds to an FSR analogue reading of 500-800. This device is sensitive to a range of $0.2N - 20N$ [62]. Arduino analogRead can take values $0 - 1023$; a total of 1024 values. Assuming a linear force to analogue conversion, we can calculate the tightness range in newtons. T_l is the lower tightness limit, T_h is the higher tightness limit:

$$T_l = \frac{500}{1024} \times 20 = 9.8N \ (2s.f)$$
$$T_h = \frac{800}{1024} \times 20 = 16N \ (2s.f)$$

The accepted band tightness range is, therefore, $9.8N - 16N$, readings outside of this range will print “too loose” and “too tight” respectively. The participants are then exposed to each of the six vibration intensities, the researcher counts off each intensity level so that participants associate each vibration intensity with a number. The participant states what their preferred intensity level would be if it were an urgent signal and they were a prosthetic user.

Participants then perform the same task under three conditions. In each condition, the task is as follows:

1. Participants receive vibrations to the arm at pseudo-random intervals.
2. Participants press the foot pedal as quickly as possible to record reaction time.
3. Participants verbally state which of the six intensity levels they think the vibration was.

The three conditions for performing this task were:

- **(a) No additional load:** Participants fully focus on reacting to vibrations
- **(b) Cognitive load:** In addition to the vibration task, participants must count out loud backwards in multiples of seven from a given series of numbers.

- **(c) Physical load:** In addition to the vibration task, participants must use the prosthetic hand and their left natural hand to assemble increasingly difficult Duplo^{TM} objects.

This allows for independent investigation into the effects of varying intensity of vibration when the user is under different levels of cognitive and physical burden. The physical load also verifies whether the signal delivery mechanism is still valid when a person is actively using the prosthetic; a key factor in ensuring this study has practical rather than purely academic merit. The condition order is systematically varied for each participant, cycling through orders *abc, acb, bac, bca, cab, cba*. This is essential as users improve at the novel vibration task throughout the study due to training; cycling the orders eliminates training bias.

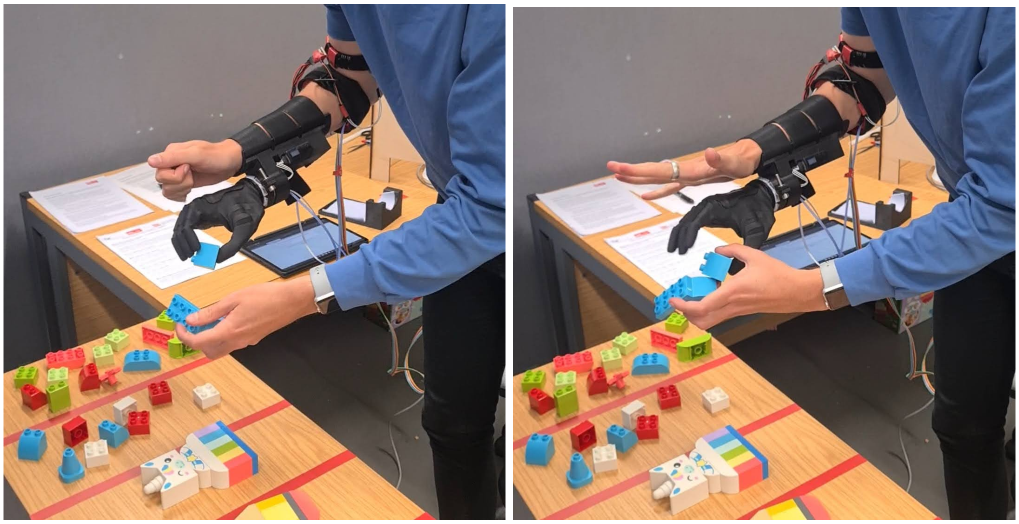
After each condition, the participant is given the same two-part questionnaire to answer. Part one is the standard NASA Task Load Index [63] to measure subjective workload in each condition. Limitations of the questionnaire form meant that an eleven-point scale was used instead of a twenty-one-point scale for this section. The second part is a questionnaire used by *Smith et al.*[64] in evaluating user experience of their vibrotactile band. Though supplementary to data collected during the condition, this will allow for analysis of whether subjective workload co-varied with actual performance in each condition, and may provide insight into the optimal feedback implementation across varying workloads.

Cognitive Load

This task was chosen to apply cognitive load due to its successful implementation (as yet unpublished) studies at the Bristol Robotics Lab by *Miles G & Smith A* [65][66]. These are yet to be published and thus cannot be cited. The same ordered list of numbers was used for each participant:

400, 824, 621, 420, 511, 344, 216, 193, 582, 961, 745, 368

Participants were asked to count backwards from each number until the subsequent vibration. If participants missed a vibration, they would not reach the end of the list.



(a) Hand Closed to Grasp (b) Hand Open to Release

Figure 3.7: The participant builds the fourth object (Rocket). Closing their hand causes the prosthetic to grasp bricks, opening their hand causes the prosthetics to release bricks.

Physical Load

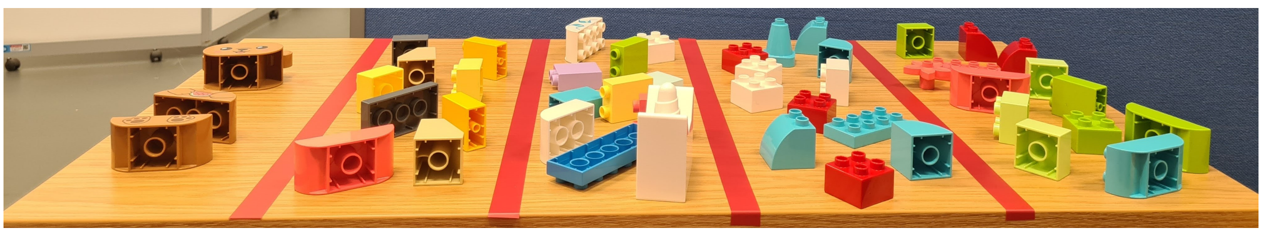
The physical task of assembling Duplo^{TM} was chosen as it is an engaging, dexterous task for the participant, the blocks are large enough to be easily grasped by the prosthetics and stick together when assembled. This reduces the likelihood that participants will lose progress by knocking over the objects, making the task less frustrating.

Figure 3.7 displays a participant during the building task. There were five objects to build in order of increasing complexity, shown in Figure 3.8. There were 48 blocks total, with the intention that participants would not be able to complete all five.

Further Design rationale

The vibrotactile motors and prosthetic actuator motors were both audible during the experiment. The option of fitting participants with headphones to prevent reactions to audio cues was considered, however a dialogue between the experimenter and participant is required during the cognitive load condition. So this potential error source was accepted. The prosthetic is capable of multiple articulated grips and switching between them. While multiple grips may provide improved dexterity for trained users, it would only serve to add further complexity to the physical load task for

(a) Building Instructions



(b) Disassembled Blocks

(c) Assembled Blocks

Figure 3.8: Instructions are marked to show the building order which corresponds to building each object left to right. The objects are segmented to avoid the task being more search than building-focused.

untrained participants in this study. Hence, the prosthetic was set with only a tripod grip, deemed the most intuitive for grasping the bricks. Participants could choose whether to use the left or right foot for the pedal. Once chosen, the pedal was adhered to a marked position and the same foot was used throughout the study. Participants remained standing throughout the study to maintain conditions for reaction time and prosthetic load on the muscles.

3.4.2 Data Collection

During each trial, several forms of data are collected. No demographic data is taken due to limitations on the ethical approval for MSc-level studies. 27 individuals participated in the study; 18 males and 9 females.

Once the participant is fitted with the hardware, the control method (Single or dual EMG) is recorded. After the participant is first exposed to the full range of vibration intensities, we record their preferred intensity for the purpose of emergency alerts for the prosthetic.

During each condition, the researcher records:

1. The participants' reaction time for each delivered vibration.
2. The participants perceived intensity for each vibration (stated verbally after pressing the pedal).
3. The actual delivered intensity for each vibration.

After each condition, the participants answer the same questionnaire detailed in the prior section. Additionally, during the physical load task, the number of bricks assembled is recorded to indicate task performance.

4 Results

4.1 Overall Performance

In the study, dual EMG control was first attempted with each participant. If the participant demonstrated a lack of controlled opening and closing of the prosthetic, this was switched to single EMG control; generally far more responsive though less dexterous. This did affect performance in the Physical load condition. 11 participants used single EMG control, assembling an average of 11.9 out of 48 bricks; 24.8%. In contrast, the 16 participants who used dual EMG assembled an average of 18.9 out of 48 bricks; 39.4%. Before each condition, participants' preferred intensity level from 1 (lowest) to 6 (highest) in the context of urgent signals, was recorded. All participants chose a level in the range of 3-6 with the overall average preferred intensity level at 4.74 $(2s.f)$.

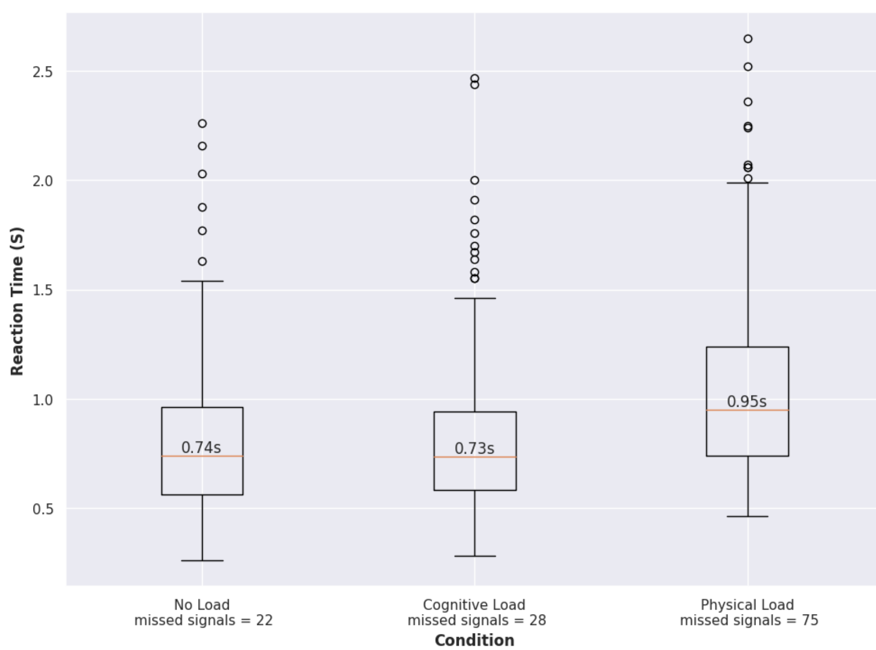


Figure 4.1: The reaction times for each condition. Any time over three seconds counted as a missed signal. There are more anomalously long reaction times (those above the upper whisker) for the two loaded conditions.

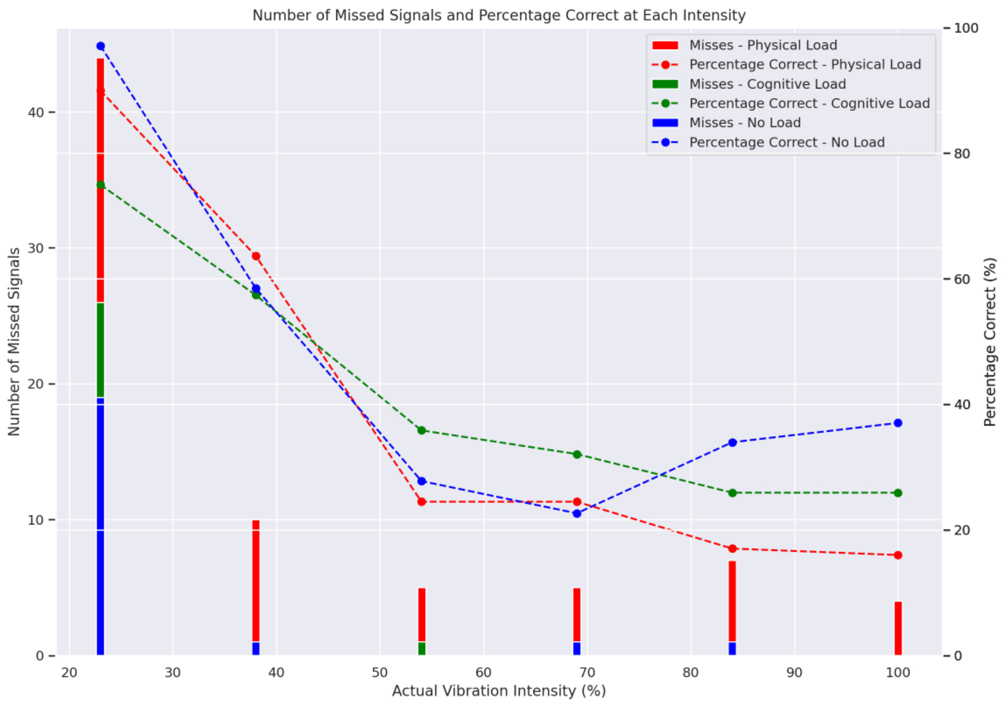


Figure 4.2: The number of missed signals across each vibration intensity and condition. More signals are missed at lower intensities and across all intensities in the physical load condition. Of the signals that were perceived, the percentage of correct judgements is shown by dashed lines. Participants were better at identifying lower-intensity vibrations.

Figure 4.1, shows that the distribution of reaction times when participants were under No or Cognitive load is similar. However, using a one-way Anova test, we find that the reaction times in the Physical load condition are significantly different ($P = 3.78 \times 10^{-20}$). Noting the number of missed signals in each condition, we find far more missed signals in the Physical condition, 75, whereas in the other conditions, the number was similar: 22 & 28 for No and Cognitive load respectively. Each condition displays a similarly sized middle two quartiles with the Physical condition having a larger spread of data overall. Anomalously slow reaction times are common in the study, these are shown as circles beyond the upper quartile whiskers.

4.2 The Influence of Varying Vibration Intensity

Looking more closely at the distribution of missed signals (Figure 4.2), we find a significant number of missed signals for each condition at the lowest vibration intensity of 24%. Above this intensity, only the Physical load condition results in multiple missed signals. Experimentally, it was observed that some of the missed signals were the result of participants taking longer than the three-second cut-off time which signified a missed signal. While it would be interesting data, we cannot compare this to the number of missed signals as a function of perceived vibration intensity since participants did not perceive the vibration in the first place.

Considering the reaction time as a function of vibration intensity, Figure 4.3 shows as a rule that increasing vibration intensity reduced participant reaction time. Here we plot the spread of reaction times at each actual and perceived intensity as well as regression lines for this data. The shaded area about each line shows the uncertainty. Looking at the actual vibration intensity, the Cognitive load condition has a sharper gradient decreasing reaction time as intensity decreases, compared to No load. This suggests that increasing intensity affects reaction time more significantly when under Cognitive load.

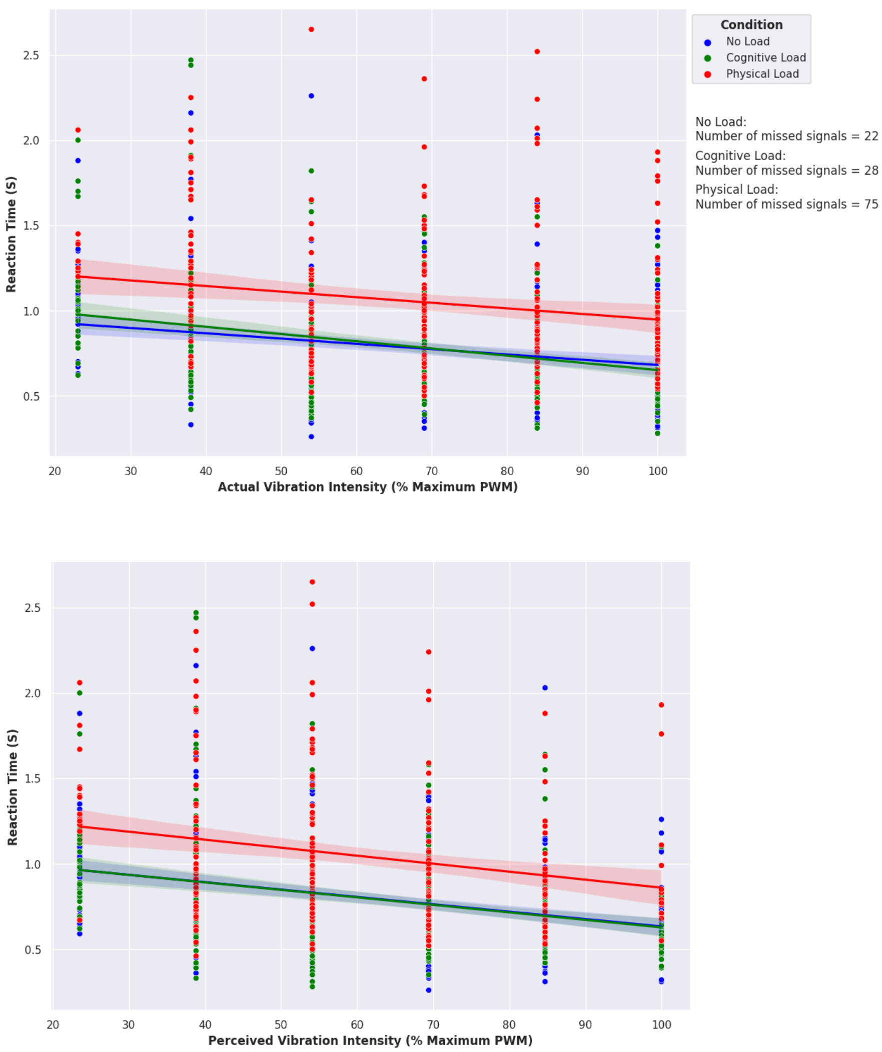


Figure 4.3: Participant reaction time across each vibration intensity and condition. The physical load condition caused longer reaction times. Reaction times for cognitive load and no load overlap across applied intensity but align near perfectly across perceived intensity.

When we measure reaction time against perceived intensity, we find that No load and Cognitive load align near perfectly. This indicates that participants react equally quickly to vibrations they believe are of the same intensity, but that the cognitive load affects their perception since the two conditions do not align when plotted against actual intensity. The Physical condition resulted in significantly slower reaction times overall, with a much greater spread of reaction time - shown by the red data points. This holds whether plotted against actual or perceived intensity. However, we can see that in the perceived intensity graph, participants judged far fewer of the vibrations to be of high intensity (84% or 100%) than the actual number delivered. This is shown by the smaller number of red data points at these intensities in the perceived graph compared to the actual intensity graph.

Figure 4.4 shows the perceived intensity as a function of the applied intensity, separated for each condition. The diagonal line on each plot displays a correct judgement of intensity. Any individually plotted points mark outliers beyond the whiskers of the box plot. In each condition, the perception for level 1 (PWM = 60) is very accurate. We should note the disparity in number of missed vibrations at this level though, significantly higher for the two loaded conditions. This means participants could identify this vibration accurately when they perceived it, but there were many instances where it was not perceived. Again, we see similar distributions for the No load and Cognitive load conditions. The Physical load condition, however, shows that participants routinely underestimated the vibration intensity, perceiving levels 5 and 6 (PWM = 216, 255) as levels 4 and 5 respectively. Participants were accurate at perceiving levels 1 and 2 but missed these signals far more than in other conditions.

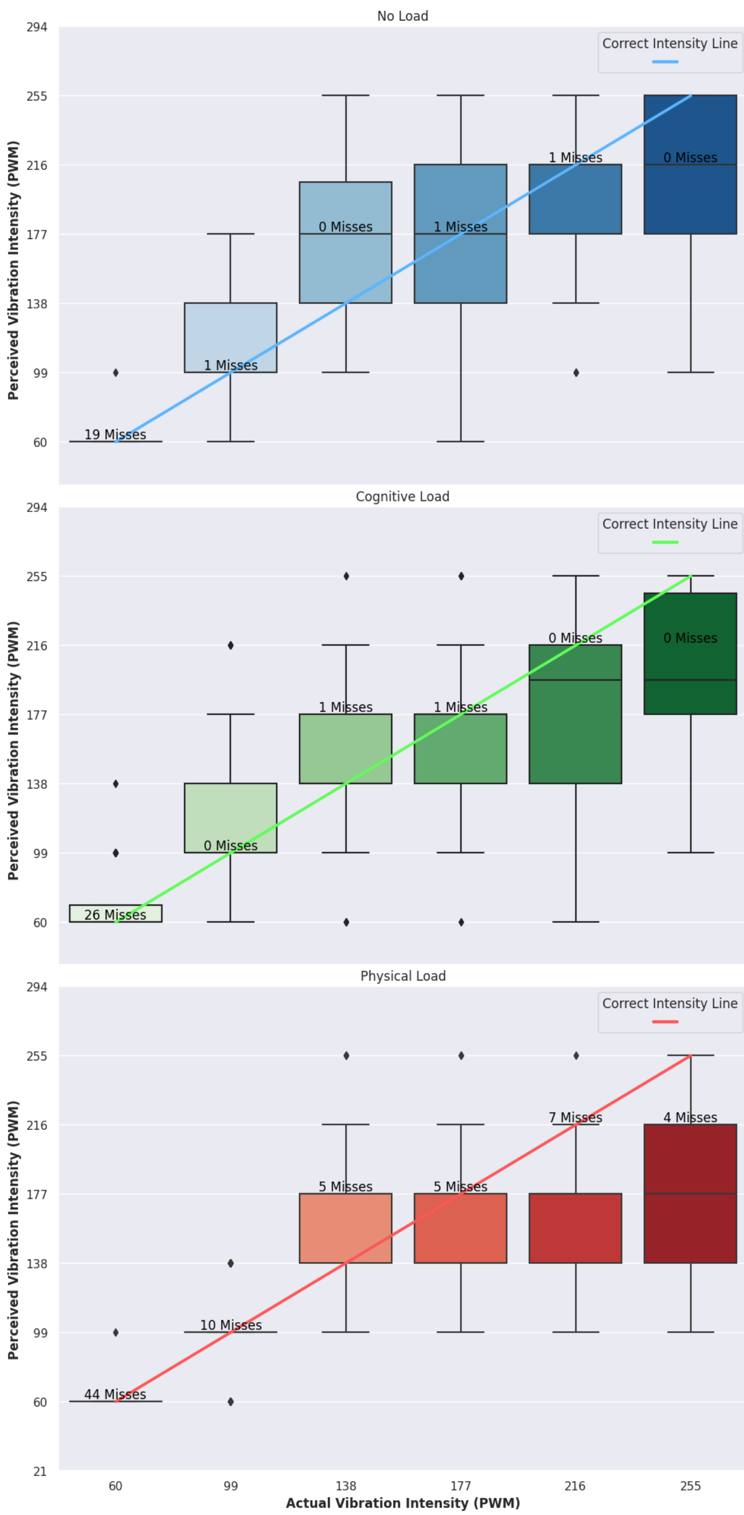


Figure 4.4: Participant perceived vs applied intensity for No Load (Blue), Cognitive Load (Green) and Physical Load (Red). The diagonal line marks correct predictions.

Statistically significant differences in perception were found across four of the six intensity levels, shown in Table 4.1. This tells us that participants perceived levels 2 and 3 more consistently across the conditions than the other four intensities, though not necessarily more accurately. Referring back to Figure 4.2, we see the percentage of correctly judged intensities in each condition. Each participant received two vibrations at each intensity, in each condition. For 27 participants, therefore, a total of 54 correct judgements are possible at each intensity, in each condition. Percentage correct judgements (J) is therefore:

$$J = \frac{Number\ Correctly\ Judged}{54 - Number\ Missed} \times 100$$

We observe a similar trend in judgement accuracy across all conditions, with levels 1 and 2 being the most distinct. When No load is applied, participants were better able to judge the highest two levels than the middle two, whereas, with either Cognitive or Physical Load, the accuracy of judgement was inversely proportional to the vibration intensity.

Intensity Level	P Value	Significant
1	0.027	Yes
2	0.33	No
3	0.69	No
4	0.00083	Yes
5	0.00043	Yes
6	0.0086	Yes

Table 4.1: We consider statistical significance as $P < 0.05$. We found that only perception of intensity levels 2 and 3 were not significantly different across conditions.

4.3 Questionnaire Results

The questionnaire results provide further interesting data on the participants' subjective experiences. Figure 4.5 shows that, as expected, mental demand rose significantly when either load was applied but only the Physical load caused an increase in physical demand. Participants found the vibrations more distracting when under load, though it should be noted that without load they were focused on the vibrations and thus may not have considered them as distractions from the task. Finally, participants rated their own performance as similar in each condition, despite Figure 4.1 indicating that performance significantly decreased in the Physical Load condition. This means participants were unaware of their slower reactions and reduced perceptive accuracy while preoccupied with a physical task. This is likely because these two performance metrics are measures of somatosensory acuity, which is diminished when stimulated by a competing physical task.

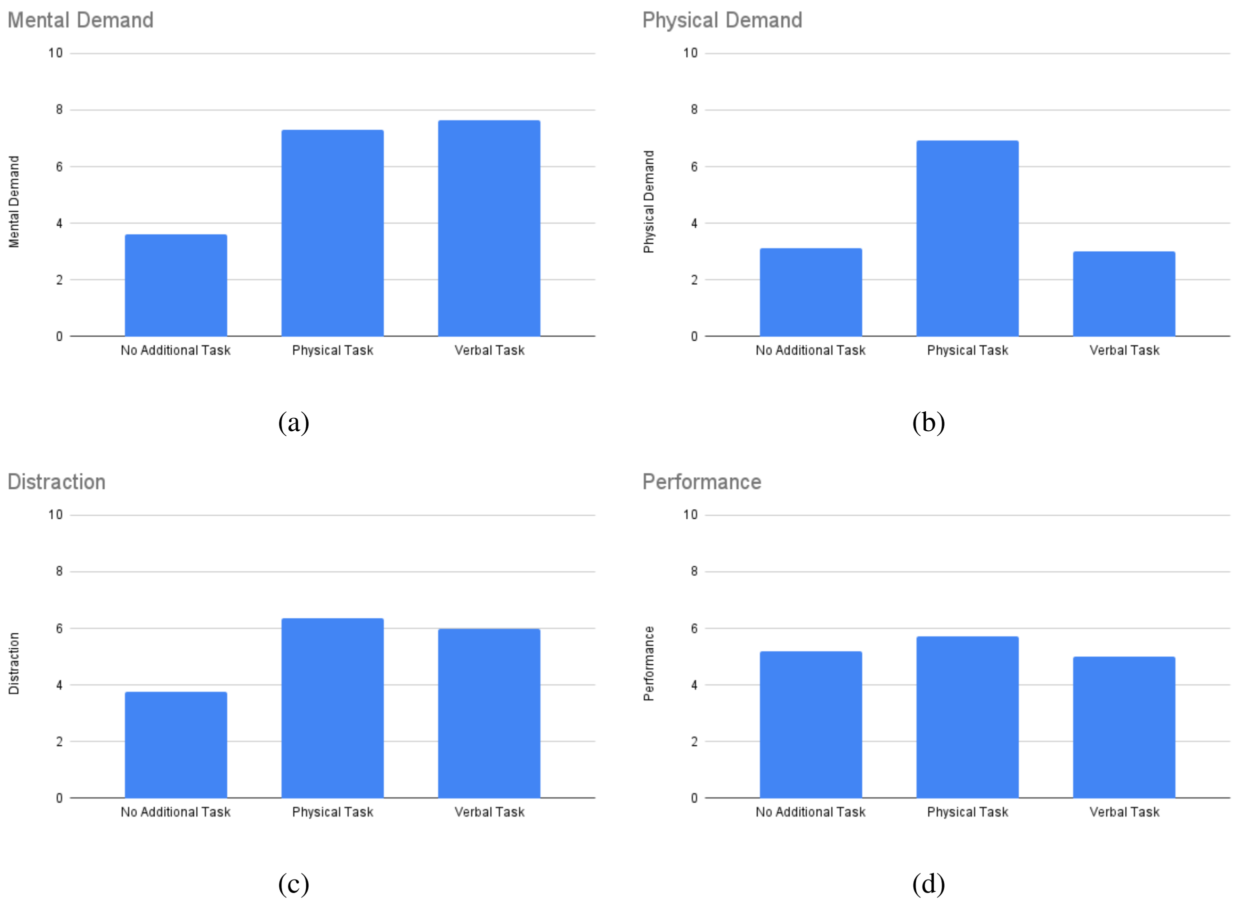


Figure 4.5: Participant average self-rating across mental demand (a), physical demand (b), how distracting vibrations were (c) and their performance in the task (d).

5 Discussion and Conclusion

5.1 Hardware Performance

Considering the time dedicated to the development of the two hardware components of this project, it is worthwhile reviewing their performance and detailing how future iterations may improve on these designs.

5.1.1 Prosthetics Platform

As stated, the performance of the prosthetic platform for same-arm dual EMG control varied from user to user. Issues were mitigated by switching the user to single EMG control, which allowed for responsive though less intuitive use. Though none were fatigued by the platform during the study, many participants commented on the weight of the device. Better weight distribution would improve the comfort and potential for unanimous dual EMG control, given it would reduce strain on the muscles being read by the EMGs. This could be achieved by offsetting the device weight, for example, tethering a counterweight over the shoulder of the participant. This would reduce mobility whilst using the device, however. Due to the natural arm being in the way, the strain on able-bodied participants using the platform will always be greater than that experienced by a prosthetic user with their own device. This is because the platform centre of mass must be further from the user. Another potential improvement would be to print the same platform design with a stiffness gradient instead of uniform stiffness. Specifically, the stiffness would remain the same for the prosthetic control panel and battery housing, but gradually decrease radially along the plastic in contact with the user's forearm. The device could then conform more tightly to each user, increasing comfort and potentially decreasing strain. Lastly, the approximation of the natural forearm as a cylinder should be abandoned. The platform diameter should be widest at the point closest to the elbow and taper inward toward the wrist; a more ergonomic design.

5.1.2 Vibrotactile Haptic Band

The vibrotactile band worked well with the marker and FSR for consistent placement and tightness, it could be improved by using a thicker band to allow more reliable adhesion. Replacing the breadboard electronics with soldered electronics would further increase the durability for future studies. More powerful motors would be required to investigate the effects of very high-intensity vibrations though as this may move toward discomfort or pain for the participant, ethical approval would need to be acquired. Switching the motors from ERM to LRA would allow researchers to control vibration frequency at a known value, while varying amplitude - a fundamental wave property - rather than vibration intensity. This would improve the integrity of experimental results as varying a compound property like intensity is conceding an element of control in the scientific study.

5.1.3 Combined Vibrotactile Feedback and Prosthetic Operation

The two hardware components could be successfully used together, though Figure 4.5 shows that doing so requires a high physical and mental demand on the user. This is undesirable since a system which takes more effort to use is more likely to be abandoned by a prosthetic user. It is worth noting however that in real use, urgent signals will be far less frequent than in the study, where simulated signals were delivered as frequently as every 15 seconds. The vibrotactile array adds negligible weight compared to the original prosthetic device and could be integrated into the fitted socket for a real prosthesis user. Actual integration with commercial prosthetics would require cooperation with the device manufacturer. This is because signals would need to be triggered using sensory data in the prosthetic hand, most commercial prosthetics do not provide their software as open-source or have official hardware interfacing capability. Improved sensory capability in most artificial hands would also be required to detect all likely sources of urgent signals.

5.2 Discussion of Study Results

Weber's Law, described in section 2.1.1, was clearly evident in our results. Figure 4.2, shows that participants correctly predicted applied vibration intensity far more accurately at the lowest two intensity levels. This supports Weber's Law as the difference in intensity Δx was identical for each subsequent level, so for the lower levels, it is more likely that $\Delta x \geq \delta x = Kx$, where K is a constant, x is the applied intensity and δx is the just noticeable difference between two intensity levels. This means it is more likely participants can distinguish and thus identify the lower intensity levels, as evidenced by the results. This suggests, that if we desire to use urgent signals of varying intensity to signify different levels of urgency or different stimuli, it is prudent to consider Weber's law. One way of doing this would be to use exponentially increasing increments between intensity levels. This would result in larger differences between higher intensity levels, making it more likely that this difference is greater than δx, allowing participants to reliably identify all levels of vibration. As urgent signals, reliable user identification is essential for their desired function to be achieved.

We must also be cognisant of the conditions under which signals were missed. Many misses occurred across all conditions for the lowest intensity level, suggesting that this is too low to be suitable for urgent signals which must not be missed. Additionally, signals were regularly missed across all intensities during the Physical load condition. This lends support to the notion that signal intensity could be adjusted based on actuator and sensor data in the hand; if the hand motors are being frequently used or the FSRs subject to frequent variances in reading, assume high Physical load and deliver higher intensities to mitigate for the lower user perception threshold. The concern identified in section 3.1 is fortunately unwarranted. Though it is true that sensor/actuator data provides no information about user cognitive load, beyond the lowest intensity level, there is no increase in missed signals when a cognitive load is applied, so the system does not need to be modulated for this condition. This means that applying the feedback optimisation solution proposed in section 3.1, using exponentially larger vibrations, is a valid implementation of the urgent signal system.

The primary argument for sending signals of varying intensity, as opposed to simply the strongest possible signal at all times, is that can convey a degree of urgency to the user. This allows the user to prioritise based on the signal received, just as those with natural hands may suffer momentary discomfort or pain to complete a certain action. Users also preferred an intensity level of 4.74 on average, so if the hand is not in use (low physical load) the system could provide a lower intensity with reasonable assuredness that the user would still perceive the signal. This would be preferable to delivering an unnecessarily strong and jarring signal. Figure 4.4 shows that, under Physical load, users perceive vibration intensities as lower than they actually are. This means that a system which indicates different urgent stimuli using different vibration intensities should increase signal level disproportionately when the user is under Physical load to deliver a signal which is perceived to be as strong as the same signal with No or Cognitive load. Bespoke user calibration would be required to achieve this implementation. As calculated in section 2.2.3, vibration intensity does not need to be minimised in an effort to conserve prosthetic battery life.

Referring back to the hypothesis made in section 3.1, we can see it has proven to be partially valid. Physical load had a clear impact on reaction time whereas Cognitive load did not. This pattern approximately holds for perceived vibration intensity, where both loaded conditions resulted in a less accurate perception of vibration intensity as the intensity was increased. For the Physical load, the quickest average reaction time was still slower than the slowest average reaction time in the unloaded condition. However, the statement that *"more intense vibrations will be required during cognitive load to achieve the same reaction time and perceptivity as without load."* is true; shown by figure 4.3.

5.3 Conclusion

Of the original objectives stated in chapter 1, we can conclusively say that all six were achieved. Both hardware systems were developed and used successfully in a user study. Though a notable limitation of the project is that LRA motors (which control for frequency variation) were not acquired and different patterns of vibration were not investigated. The results of this study were then presented and analysed to propose an optimal implementation of vibrotactile urgent signals for use with actuated upper-limb prostheses. The study showed little impact on reaction times or perception when comparing unloaded to Cognitive load conditions, but a statistically significant increase in reaction time and decrease in perceptive accuracy during the Physical load condition. Perceptive accuracy was also generally inversely proportional to the applied vibration intensity, providing evidence for Weber's Law in action given the constant difference in intensity between consecutive levels. The optimal solution proposed is to exponentially increase the difference in intensity between increasing levels to mitigate the effects of Weber's Law thus improving user discretion of the different levels. Additionally, sensor and actuator data from the prosthetic device should be used to indicate a measure of Physical load on the user, where a high Physical load stimulates signals of greater intensity across all intensity levels. This mitigates the effects of user tendency to underestimate signal intensity when under a Physical load.

If this proposed implementation were used in earnest, future work would seek to trigger urgent signals by sensor readings in the prosthetic device so its reliability could be formally studied. This would require the cooperation of the device manufacturer. If it proved to provide users with reliably perceptible and understandable signals, it would form the basis of a device safety system that effectively substitutes for pain; allowing users to confidently train using their device without visual confirmation. Restoring any measure of non-visual operation using the artificial limb is another step to achieving the proprioceptive, fine-dexterity control inherent to the natural human hand.

A Appendix

Here you can find the appendices referenced throughout the dissertation.

A.1 Experiment Procedure

Experiment Procedure

The following provides the step-by-step procedure for the human study carried out as part of the dissertation of Finlo Heath, MSc Robotics.
(Dated: August 1, 2023)

I. INTRODUCTION

When you first meet the participant, you must carry out the following steps:

1. Greet participants with a consistent positive mood. Your sentiment can affect their perception of the study trials.
2. Give the participant the information sheet and have them read it carefully.
3. check that they understand all the information there.
4. hand them the privacy statement to read through.
5. Finally, provide them with the informed consent form to sign if they are happy.

II. EXPLAIN AND DEMONSTRATE

Once the participant has signed the consent form:

1. Explain the underlying task: Whenever the participant notices a vibration on the arm, press the foot pedal as swiftly as possible. After this, they will verbally provide the researcher with a value for the intensity of the vibration signal ranging from 1 LOWEST to 6 HIGHEST. They are trying to estimate the intensity level correctly. We will see if their perception of intensity is affected by load.
2. Provide verbal confirmation that there will be three conditions. Explain the following cognitive load tasks:
   - Counting backwards in multiples of 7.
   - Building task with Duplo.
3. Check again with participants whether they are happy they understand the tasks. Do not proceed until they do.

III. HARDWARE SET UP

1. Ensure the hand resting station is in place for the user.
2. Strap the vibrotactile sleeve to the participant and ensure no pinching. Align as specified on the band.
3. Strap the EMG band on the participant, best guess on placement.
4. Strap hand to the participant, wrist just beyond contact, tight.
5. Turn the hand on. Launch Covvi Go, check config set to *participant*. Check the signals.

6. Adjust electrode band until clear signals for both. Then calibrate for the user.
7. Check hand responsive and the user happy. If not, repeat steps 5 and 6 until working.
8. Ensure vibrotactile feedback and foot-pedal working, use test script for this.
9. Duplo pieces should be disassembled but not shuffled.

IV. TRAINING & CALIBRATION

1. Run *VibrationCalibration* script.
2. Perform FSR band tightness check.
3. Deliver the six intensities three times over with one-second intervals.ASK USER **"In the context of an urgent signal for the prosthetic, which intensity do you prefer out of the six?"**. Record the answer.
4. give the user some time to practice with the pedal.
5. give the user some time to practice controlling the hand (NOT BUILDING).

V. SELECT CONDITION ORDER

Choose the condition order: abc, acb, bac, bca, cab, cba.

1. Record the condition order.
2. Inform the participant.
3. Move to the appropriate section below.

VI. CONDITION A: NO COGNITIVE LOAD

For this condition, we apply the following steps:

1. At pseudo-random intervals, apply vibrotactile feedback to the user.
2. Feedback will be of different intensity levels, 1-6.
3. When they notice the feedback, the user must press the foot pedal as quickly as possible.
4. Researcher records:
   - time stamp of each signal.
   - Intensity value of the signal from 1-6.
   - user time to respond. Specific recording value for missed signal.
   - user perceived rating of intensity from 1 (Lowest) to 6 (Highest). Specific recording value for missed signal.
5. Researcher gives user questionnaire.

VII. CONDITION B: VERBAL TASK

For this condition, we apply the following steps:

1. Participant counts backwards in increments of seven from a set list of numbers.
2. After each vibration, they are given a new number to avoid them having to remember where they were.
3. Steps 1-4 of section VI repeated while they perform this task.
4. Researcher gives user questionnaire.

VIII. CONDITION C: PHYSICAL TASK TASK

For this condition, we apply the following steps:

1. Participant uses their left natural hand and right prosthetic hand to follow the instructions and build a Duplo set. Rules are: **covvi hand must pick up the blocks but can pass to left natural hand. Building must occur in the air - no bracing against the table. You are not allowed to use your right natural hand at any point.**

2. Steps 1-4 of section VI repeated while they perform this task. In addition, the researcher records build task performance. Specifically, the number of bricks assembled out of the total provided. This aims to encourage participants not to ignore progress in the task, and to give it their full attention.

3. Researcher gives user questionnaire.

IX. USER DE-BRIEF

Once the user has completed both conditions:

1. Unstrap the user from all hardware and place the hand back in the resting station.

2. Provide the user with a reminder of the privacy policy and their right to withdraw their data within seven days.

3. Answer any further questions they have and reward them with a sweet if they would like one.

A.2 Participant Facing Documentation

Participant Information Sheet

Study Title: Protecting Prosthetics: Vibrotactile Haptic Feedback as Urgent Signals Under Cognitive Load

PLEASE READ THIS SHEET IN ITS ENTIRETY

You are invited to take part in research taking place at the Bristol Robotics Laboratory. Before you decide whether to take part, it is important for you to understand why the study is being done and what it will involve. Please read the following information carefully and if you have any queries or would like more information, please contact Finlo Heath, Faculty of Environment and Technology, Bristol Robotics Laboratory, University of the West of England, Bristol, finlo.heath.2022@bristol.ac.uk.

Who is organising the research?

The project is led by Finlo Heath, MSc Robotics at Bristol University. Dr Ben Ward-Cherrier & Dr Martin Pearson are the supervisors for this research. Please find their details at the end of this document.

What is the aim of the research?

The overall aim of the research is to investigate the use of vibrotactile haptic (touch) feedback, in conjunction with prosthetics hands. If prosthesis users notice the vibrations and react quickly even under cognitive load, they could have useful applications as an urgent signal mechanism. These signals could warn of potential imminent damage to these expensive devices, helping improve user care of the device.

The purpose of this study is to test whether users can notice and localise the vibrotactile signals under cognitive load equally proficiently as when no cognitive load is applied. In addition, different signal variances will be tested to see if any produce superior reaction time and localisation.

Why have I been invited to take part?

Any adult individual is a suitable candidate for this study, provided they are aware of local health and safety procedures in the BRL as well as current Covid-19 guidelines.

Do I have to take part?

You do not have to take part in this research. It is up to you to decide whether or not you want to be involved. If you do decide to take part, you will be given a copy of this information sheet to keep and will be asked to sign a consent form. If you do decide to take part, you are free to stop and withdraw from the study at any time without giving a reason.

What will happen to me if I take part and what do I have to do?

You will first be asked to sign a consent form, read a privacy notice, and provide some basic demographic information. You will then be fitted with an EMG controlled Prosthetic arm, mounted with an attachment for able-bodied users. Once fitted, and control of the arm verified, you will then take part in three experiment trials. In each you will aim to notice a vibrotactile signal when received and press a pedal to indicate this. In condition A, you will focus only on this task. In condition B & C, you will have an additional task requiring use of the robotic hand. After these trials, you will provide responses to a questionnaire. The order of conditions may be either A,B,C or A,C,B.

The study will take approximately *30* minutes.

Data will be gathered using the following methods:

Questionnaires

- After each of the two trials, you will provide responses via a digital questionnaire. Your responses will be anonymised.

Written Feedback/Comments

- The researcher may record statements made by the participant outside of the questionnaire, with the participants consent.

Task Performance

- The reaction time to vibrotactile signals being sent, will be recorded.
- The performance in each of the tasks during condition B.

What are the possible risks of taking part?

The study is considered low risk. However, there is a small risk of physical strain given the weight of the robotic hand which is mounted on the right forearm. Rest between use is included within the study to mitigate this risk. If you have been advised by a doctor not to participate in physical activity, please inform the researcher before agreeing to take part in the study, to discuss whether doing so is safe.

What will happen to your information?

All the information we receive from you will be treated in the strictest confidence.
All the information that you give will be kept confidential and anonymised. You will be assigned a participant ID that you can use to request the removal of your data from the study up to 7 days after completion of the experiment. After this point, the anonymised data will be analysed, and we will ensure that there is no possibility of identification or re-identification from this point.

Hard copy material (the consent form) will be kept in a locked and secure setting to which only the researchers will have access in accordance with the University's and the Data Protection Act 2018 and General Data Protection Regulation (GDPR) requirements.

Where will the results of the research study be published?

The results of this usability study will be reported in the MSc Dissertation of Finlo Heath. In addition, this may be submitted for journal publishing. If accepted, it then may be publicly available.

Who has ethically approved this research?

Ethical approval for this project falls under the Pre-approval granted for MSc Robotics studies on the module EMATM0055. For further details, please contact grp-dissertation_unit_2022@groups.bristol.ac.uk.

What if something goes wrong?

If you have any questions about the ethical conduct of this research, have any complaints or concerns, or are uncertain about any aspect of your participation please contact the project supervisors or the University's research ethics committee.

Project Supervisor:
Dr Ben Ward-Cherrier, b.ward-cherrier@bristol.ac.uk

What if I have more questions or do not understand something?

If you would like any further information about the research, please contact in the first instance:

Finlo Heath, finlo.heath.2022@bristol.ac.uk
Dr Ben Ward-Cherrier, b.ward-cherrier@bristol.ac.uk

Thank you for agreeing to take part in this study. You will be given a copy of this Participant Information Sheet and your signed Consent Form to keep.

Privacy Notice

Study Title: Protecting Prosthetics: Vibrotactile Haptic Feedback for Source Discrimination of Urgent Signals Under Cognitive Load

Purpose of the Privacy Notice

This privacy notice explains how the University of the West of England, Bristol (UWE) collects, manages and uses your personal data before, during and after you participate in this focus group. 'Personal data' means any information relating to an identified or identifiable natural person (the data subject). An 'identifiable natural person' is one who can be identified, directly or indirectly, including by reference to an identifier such as a name, an identification number, location data, an online identifier, or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural or social identity of that natural person.

This privacy notice adheres to the General Data Protection Regulation (GDPR) principle of transparency. This means it gives information about:

- How and why your data will be used for the research;
- What your rights are under GDPR; and
- How to contact UWE Bristol and the project lead in relation to questions, concerns or exercising your rights regarding the use of your personal data.

This Privacy Notice should be read in conjunction with the Participant Information Sheet and Consent Form provided to you before you agree to take part in the research.

Why are we processing your personal data?

UWE Bristol undertakes research under its public function to provide research for the benefit of society. As a data controller we are committed to protecting the privacy and security of your personal data in accordance with the (EU) 2016/679 the General Data Protection Regulation (GDPR), the Data Protection Act 2018 (or any successor legislation) and any other legislation directly relating to privacy laws that apply (together "the Data Protection Legislation"). General information on Data Protection law is available from the Information Commissioner's Office (https://ico.org.uk/).

How do we use your personal data?

We use your personal data for research with appropriate safeguards in place on the lawful bases of fulfilling tasks in the public interest, and for archiving purposes in the public interest, for scientific or historical research purposes.

We will always tell you about the information we wish to collect from you and how we will use it.

We will not use your personal data for automated decision making about you or for profiling purposes.

Our research is governed by robust policies and procedures and, where human participants are involved, is subject to ethical approval from either UWE Bristol's Faculty or University Research Ethics Committees. This research has been approved by UWE Bristol's Ethics Committee. The research team adhere to the **Ethical guidelines of the British Educational Research Association (and/or the principles of the Declaration of Helsinki, 2013) and the principles of the General Data Protection Regulation (GDPR).**

For more information about UWE Bristol's research ethics approval process please see our Research Ethics webpages at:
www1.uwe.ac.uk/research/researchethics

What data do we collect?

The data we collect will vary from project to project. Researchers will only collect data that is essential for their project. The specific categories of personal data processed are described in the Participant Information Sheet provided to you with this Privacy Notice.

Who do we share your data with?

We will only share your personal data in accordance with the attached Participant Information Sheet and your Consent.

How do we keep your data secure?

We take a robust approach to protecting your information with secure electronic and physical storage areas for research data with controlled access. If you are participating in a particularly sensitive project UWE Bristol puts into place additional layers of security. UWE Bristol has Cyber Essentials information security certification.

Alongside these technical measures there are comprehensive and effective policies and processes in place to ensure that users and administrators of information are aware of their obligations and responsibilities for the data they have access to. By default, people are only granted access to the information they require to perform their duties. Mandatory data protection and information security training is provided to staff and expert advice available if needed.

How long do we keep your data for?

Your personal data will only be retained for as long as is necessary to fulfil the cited purpose of the research. The length of time we keep your personal data will depend on several factors including the significance of the data, funder requirements, and the nature of the study. Specific details are provided in the attached Participant Information Sheet. Anonymised data that falls outside the scope of data protection legislation as it contains no identifying or identifiable information may be stored in UWE Bristol's research data archive or another carefully selected appropriate data archive.

Your Rights and how to exercise them

Under the Data Protection legislation you have the following **qualified** rights:

(1) The right to access your personal data held by or on behalf of the University;
(2) The right to rectification if the information is inaccurate or incomplete;
(3) The right to restrict processing and/or erasure of your personal data;
(4) The right to data portability;
(5) The right to object to processing;
(6) The right to object to automated decision making and profiling;
(7) The right to complain to the Information Commissioner's Office (ICO).

Please note, however, that some of these rights do not apply when the data is being used for research purposes if appropriate safeguards have been put in place.

We will always respond to concerns or queries you may have. If you wish to exercise your rights or have any other general data protection queries, please contact UWE Bristol's Data Protection Officer (dataprotection@uwe.ac.uk).

If you have any complaints or queries relating to the research in which you are taking part please contact either the research project lead, whose details are in the attached Participant Information Sheet, UWE Bristol's Research Ethics Committees (research.ethics@uwe.ac.uk) or UWE Bristol's research governance manager (Ros.Rouse@uwe.ac.uk)

v.1: This Privacy Notice was issued in April 2019 and will be subject to regular review/update.

Consent Form

Study Title: Protecting Prosthetics: Vibrotactile Haptic Feedback for Source Discrimination of Urgent Signals Under Cognitive Load

This consent form will have been given to you with the Participant Information Sheet. Please ensure that you have read and understood the information contained in the Participant Information Sheet and asked any questions before you sign this form. If you have any questions please contact a member of the research team, whose details are set out on the Participant Information Sheet.

If you are happy to take part in this study, please sign and date the form. You will be given a copy to keep for your records.

Please read the statements below and sign below to give consent:

I have read and understood the information sheet
I have been given the opportunity to ask questions and have had my questions answered to my satisfaction.
I am aware of the risks and benefits of taking part in the study
I am aware that data collected will be anonymised, kept in accordance with General Data Protection Regulation (GDPR), and will be viewed and analysed by the research team as part of their studies.
I am aware that I have the right to withdraw consent and discontinue participation without penalty before or during the study.
I am aware that I have the right to withdraw my data from the experiment up to 7 days after the completion of the experiment, using the participant ID that the researcher will provide.
I have freely volunteered and am willing to participate in this study.
I am willing to have my questionnaire responses collected.

Name (Printed)……………………………………………………………………………

Signature……………………………………………………. Date…………………….

Protecting Prosthetics: Questionnaire

This questionnaire will be completed three times by each participant. Once after each condition.

Not shared

* Indicates required question

Participant ID *

Your answer

Condition *

- No Additional Task
- Verbal Task
- Physical Task

Next

Clear form

NASA Task Load Index

Please indicate **how challenging the task was** based on the following criteria:

Mental Demand

	0	1	2	3	4	5	6	7	8	9	10	
Low	○	○	○	○	○	○	○	○	○	○	○	High

Physical Demand

	0	1	2	3	4	5	6	7	8	9	10	
Low	○	○	○	○	○	○	○	○	○	○	○	High

Temporal Demand

	0	1	2	3	4	5	6	7	8	9	10	
Low	○	○	○	○	○	○	○	○	○	○	○	High

Performance

	0	1	2	3	4	5	6	7	8	9	10	
Good	○	○	○	○	○	○	○	○	○	○	○	Poor

Effort

	0	1	2	3	4	5	6	7	8	9	10	
Low	○	○	○	○	○	○	○	○	○	○	○	High

Frustration Level

	0	1	2	3	4	5	6	7	8	9	10	
Low	○	○	○	○	○	○	○	○	○	○	○	High

Back Next Clear form

Vibrotactile Feedback Evaluation

Please rate the following statements by **how much you agree with them about the vibration feedback method you experienced,** in the context of the task performed:

It is easy to understand.

	0	1	2	3	4	5	6	7	8	9	10	
Disagree	○	○	○	○	○	○	○	○	○	○	○	Agree

It is distracting.

	0	1	2	3	4	5	6	7	8	9	10	
Disagree	○	○	○	○	○	○	○	○	○	○	○	Agree

It is user friendly.

	0	1	2	3	4	5	6	7	8	9	10	
Disagree	○	○	○	○	○	○	○	○	○	○	○	Agree

Using it is effortless.

	0	1	2	3	4	5	6	7	8	9	10	
Disagree	○	○	○	○	○	○	○	○	○	○	○	Agree

It is difficult to learn to use it.

	0	1	2	3	4	5	6	7	8	9	10	
Disagree	○	○	○	○	○	○	○	○	○	○	○	Agree

It works the way I want it to work.

	0	1	2	3	4	5	6	7	8	9	10	
Disagree	○	○	○	○	○	○	○	○	○	○	○	Agree

Back Submit Clear form

A.3 Arduino Code

A.3.1 Calibrate

This file is used to confirm the analog FSR reading is within a small range of values (500-800) which indicates a roughly consistent band tightness across participants. It then delivers the user each intensity level, three times over, to introduce them to the range of intensities.

```
// constants won't change. They're used here to set pin numbers:

// const int FINISHEDbuttonPin = 3;
const int ledPin = 13;     // the number of the LED pin
const int NumOfEvents = 18; // how many times do we buzz the participants
const int motorPin = 3;
const int motorPin2 = 4;
const int motorPin3 = 5;
const int motorPin4 = 6;
int fsrPin = 0;      // the FSR and 10K pulldown are connected to a0

// variables will change:
int fsrReading;      // the analog reading from the FSR resistor divider
int FINISHEDbuttonState = 0;
float Time = 0;
float currentStopwatch = 0;
float StopTimesArray[NumOfEvents];
int MotorPWMArray[NumOfEvents] = {60, 99, 138, 177, 216, 255, 60, 99, 138,
    177, 216, 255, 60, 99, 138, 177, 216, 255};
bool shuffled = false;
int timesStopped = 0;
int StartClock = random(17,25);

void setup() {
  // initialize the LED pin as an output:
  pinMode(ledPin, OUTPUT);
  // initialize the pushbutton pin as an input:
  pinMode(motorPin, OUTPUT);
```

```
  pinMode(motorPin2, OUTPUT);
  pinMode(motorPin3, OUTPUT);
  pinMode(motorPin4, OUTPUT);
  Serial.begin(9600);
  delay(1000);
  Serial.println("*** NEW TRIAL ***");
}

void loop() {
while(Serial.available() == 0) { // once enter is pressed, this condition
    will no longer be satisfied.
  fsrReading = analogRead(fsrPin);

  Serial.print("Analog reading = ");
  Serial.print(fsrReading);     // print the raw analog reading

  if (fsrReading < 30) {
    Serial.println(" - No pressure");
  } else if (fsrReading < 500) {
    Serial.println(" - Too Loose");
  } else if (fsrReading < 800) {
    Serial.println(" - Correct Tightness Range");
  } else {
    Serial.println(" - Too Tight");
  }


  }

    if (timesStopped < NumOfEvents) {
    vibrate(Time, StartClock, motorPin, MotorPWMArray[timesStopped]);
    vibrate(Time, StartClock, motorPin2, MotorPWMArray[timesStopped]);
    vibrate(Time, StartClock, motorPin3, MotorPWMArray[timesStopped]);
    vibrate(Time, StartClock, motorPin4, MotorPWMArray[timesStopped]);
    timesStopped+=1;
    Serial.println(timesStopped);
    delay(1000);
```

```
      digitalWrite(motorPin,LOW);
      digitalWrite(motorPin2,LOW);
      digitalWrite(motorPin3,LOW);
      digitalWrite(motorPin4,LOW);
      delay(1000);
      }
  }

// I am using motors 1,2,3,4
// Function to control the vibration of the motor
void vibrate(float time, float startingTime, int motor, int pwm) {
  float vibrateUntil = startingTime + 0.5;  // Calculate the time until
    which the motor should vibrate (0.5 seconds)

  if (Time < vibrateUntil) {
    analogWrite(motor, pwm);  // Turn on the motor vibration
  } else {
    digitalWrite(motor, LOW);   // Turn off the motor vibration
    }
  }
```

Listing A.1: calibrate.ino

A.3.2 RunCondition

This file is used to record reaction times and delivered intensities for vibrations felt by the user. Each intensity is delivered twice in a random order, with pseudo-random time intervals between each vibration. If more than three seconds passes after a vibration without the user pressing the pedal, it is considered a missed signal.

```
// constants won't change. They're used here to set pin numbers:
const int buttonPin = 2;  // the number of the pushbutton pin
// const int FINISHEDbuttonPin = 3;
const int ledPin = 13;    // the number of the LED pin
const int NumOfEvents = 12; // how many times do we buzz the participants
const int motorPin = 3;
```

```
const int motorPin2 = 4;
const int motorPin3 = 5;
const int motorPin4 = 6;

// variables will change:
int buttonState = 0;  // variable for reading the pushbutton status
int FINISHEDbuttonState = 0;
float Time = 0;
float currentStopwatch = 0;
float StopTimesArray[NumOfEvents];
int MotorPWMArray[NumOfEvents] = {60, 99, 138, 177, 216, 255, 60, 99, 138,
    177, 216, 255};
bool shuffled = false;
int timesStopped = 0;
int StartClock = random(17,25);


void setup() {
  // initialize the LED pin as an output:
  pinMode(ledPin, OUTPUT);
  // initialize the pushbutton pin as an input:
  pinMode(buttonPin, INPUT);
  pinMode(motorPin, OUTPUT);
  pinMode(motorPin2, OUTPUT);
  pinMode(motorPin3, OUTPUT);
  pinMode(motorPin4, OUTPUT);
  Serial.begin(9600);
  delay(1000);
  Serial.println("*** NEW TRIAL ***");
}

void loop() {
  randomSeed(analogRead(A0)); // Analog read on an unused analog pin
     gives the random floating voltage noise on that pin.
  // Fill the motor intensities list in a random order
  if (shuffled == false) {
```

```
    shuffled = true;
    for (int i=0; i < NumOfEvents; i++) {

    int r = random(i, NumOfEvents);
    int temp = MotorPWMArray[i];
    MotorPWMArray[i] = MotorPWMArray[r];
    MotorPWMArray[r] = temp;
    Serial.println(MotorPWMArray[i]);
  }

  }

  // check time and button state
  Time = float(millis())/float(1000);
  // read the state of the pushbutton value:
  buttonState = digitalRead(buttonPin);

  // Conditions to Stop the loop
  // STOPSTOPSTOPSTOP

  if (timesStopped == NumOfEvents) {
    Serial.println("***ReactionTimes***");

    // Iterate over the StopTimesArray to print the recorded reaction
   times
    for (int i = 0; i < NumOfEvents; i++) {
      if (StopTimesArray[i] == 100.0) {
        Serial.print("Signal Missed");  // Print "Signal Missed" if the
   reaction time is 100.0
        Serial.print(", ");
        // Serial.print("   , Intensity (% PWM) = ");
        Serial.print((MotorPWMArray[i]*100)/255);
        Serial.print(", ");
        Serial.println(MotorPWMArray[i]);
      } else {
        // Serial.print("Time (s) =  ");
```

```
        Serial.print(StopTimesArray[i]);  // Print the recorded reaction time
        Serial.print(", ");
        // Serial.print("  , Intensity (% PWM) = ");
        Serial.print((MotorPWMArray[i]*100)/255);
        Serial.print(", ");
        Serial.println(MotorPWMArray[i]);
      }
    }
    timesStopped += 1;  // Increment the timesStopped variable by 1
}

  else if (timesStopped > NumOfEvents){
    return;
  }
  // STOPSTOPSTOPSTOP


  // Condition to wait until reaching the start time
  else if (Time < StartClock){ // should work on the grounds that time list increases in order.
  // turn the stopwatch on to indicate to the user that they should react

  digitalWrite(ledPin, LOW);
  return;
  }
  // Once start time is reached
  else{
  digitalWrite(ledPin, HIGH);
  vibrate(Time, StartClock, motorPin, MotorPWMArray[timesStopped]);
  vibrate(Time, StartClock, motorPin2, MotorPWMArray[timesStopped]);
  vibrate(Time, StartClock, motorPin3, MotorPWMArray[timesStopped]);
  vibrate(Time, StartClock, motorPin4, MotorPWMArray[timesStopped]);

if (buttonState == HIGH) {
  // turn LED on:
```

```
    digitalWrite(ledPin, LOW);

    float pressTime = currentStopwatch;  // Store the current stopwatch value as the press time
    StopTimesArray[timesStopped] = pressTime;  // Store the press time in the StopTimesArray

    StartClock = StartClock + random(15,20);  // Adjust the StartClock for the next event

    timesStopped += 1;  // Increment the timesStopped variable by 1

    digitalWrite(motorPin, LOW);  // Turn off the motors
    digitalWrite(motorPin2, LOW);
    digitalWrite(motorPin3, LOW);
    digitalWrite(motorPin4, LOW);

    // Now wait for serial input while the participant provides a pleasantness rating.
    Serial.read(); // set available back to zero
    // Serial.println(Serial.available());
    Serial.println("Waiting For input");
    while(Serial.available() == 0) { // once enter is pressed, this condition will no longer be satisfied.

      }
    Serial.println("Input received.");
    Serial.read(); // set available back to zero
    // Serial.println(Serial.available());
    return;  // Exit the function
  }

  // If they take longer than 3 seconds, mark the signal as missed.
  else if (currentStopwatch > 3.0) {
    digitalWrite(ledPin, LOW);  // Turn off the LED.
    Serial.println("**************** Signal Missed ***************");
```

```
  StopTimesArray[timesStopped] = 100.0;  // Mark the signal as missed by
    assigning 100.0 to the corresponding index in StopTimesArray.

  StartClock = StartClock + random(15,20);  // Adjust the StartClock for
    the next event.

  timesStopped += 1;  // Increment the timesStopped variable by 1.

  digitalWrite(motorPin, LOW);  // Turn off the motors
  digitalWrite(motorPin2, LOW);
  digitalWrite(motorPin3, LOW);
  digitalWrite(motorPin4, LOW);

  currentStopwatch = 0.0;  // Reset currentStopwatch to 0.0 to avoid
    immediate triggering of this condition on subsequent buzzes.

  return;  // Exit the function.
}

    else {
    // turn LED off:
    currentStopwatch = float(millis())/float(1000) - StartClock;
    // Serial.println(currentStopwatch);
    }
    }
  }





// I am using motors 1,2,3,4
// Function to control the vibration of the motor
void vibrate(float time, float startingTime, int motor, int pwm) {
  float vibrateUntil = startingTime + 0.5;  // Calculate the time until
```

```
    which the motor should vibrate (0.5 seconds)

  if (Time < vibrateUntil) {
    analogWrite(motor, pwm);  // Turn on the motor vibration
  } else {
    digitalWrite(motor, LOW);   // Turn off the motor vibration
    }
  }
```

Listing A.2: RunCondition.ino

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