Audio Sensory Substitution for Human-in-the-loop Force Feedback of Upper Limb Prosthetics

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***Abstract*—Users of prosthetic hands, such as upper limb amputees, require tactile feedback and sensation to successfully achieve complex gripping and grasping tasks. Whilst there are many methods of electronically capturing this interaction (through electronic pressure sensor arrays) there are limited methods of interfacing this data with the human brain. Somatotopical approaches do exist, however these are typically very invasive, and rely on access to the nerve. As an alternative approach, this paper investigates sensory substitution, whereby the user's sense of sound is exploited as a feedback interface between the sensors and the brain. A study, consisting of 8 participants, and a randomized trial method, is used to determine the perceptual latency and range sensitivity across a series of modulation techniques including frequency, volume, and beating. Two of these were used simultaneously to determine if two degrees of freedom were able to be comprehended simultaneously. It is found that multi-channel audio feedback is suitable for low bandwidth feedback applications so long as it can deal with latency of at least 600 ms. The capability of this interface has been captured in terms of time delay, learning curve, task correlation, and accuracy.**

***Index Terms*—Medical, mechatronics, feedback, audio, prosthetics.**

I. Introduction

Amputation of the hand, or extremities of the upper limb, affects 0.014% of the New Zealand population [1] and more prevalently, 0.18% of the US population [2]. In order to maintain a higher quality of life, it is desirable that these patients are fitted with active prosthetics. For these to work harmoniously with the brain, descending actuation commands, and ascending sensory feedback, are required. Thus, two interfaces need to exist between electro-mechanical elements of prostheses and the proposed controller: the human brain.

The capability of commercially-available active prosthetic hands, such as [3], [4], are realized by complex mechatronic systems. Some having five or more input degrees of freedom, with individually controllable fingers. Open loop control of such prosthetics is typically achieved by intercepting neural pathways descending from the brain(eg. Electromyography, such as in [5], [4], and is well understood. However, this only restores the motor dexterity of the prosthetic, and does not address the missing proprioceptive and exteroceptive sensory feedback information that are typically supplied by the hand [3]. This feedback is required to complete the closed loop control with the 'brain in the loop' [6].

It is important to note that amputation not only removes significant portions of the limb's motor functionality [7]; but also severs the connection between the brain and mechanoreceptors of the hand and fingers [3], [8]. It is these receptors that usually provide the sense of touch via the somatosensory system [9], [10], which are necessary for control of gripping and grasping tasks. Without this information, the ability of the prosthetic is decreased and people may have difficulty with everyday activities such as the manipulation of objects [11]. The mechanoreceptors themselves can be replaced; force and pressure stimuli can be readily measured by electronic sensors that can be fixed at important sites on the prosthetic. However, an interface is required to convert this electronic signal into something that the brain can understand. There are two main methods of providing tactile feedback from electronic systems to the brain; they are known as somatotopical, and non-somatotopical, methods respectively [7], [6].

Direct somatotopical feedback involves stimulating the sensory neural structures that are physiologically involved in function of the hand [3]. Two such techniques use electrodes to either stimulate nerves that present as phantom digit areas on an amputee's stump surface [6], or stimulate subcutaneously, which involves invasive surgical procedures and implantable electrodes [3], [12]. These techniques, and their surgical procedures, are not always successful. Thus, sensory substitution (by non-somatotopical methods) is a desirable alternative.

Non-somatotopical feedback techniques involve stimulation of alternative sensory pathways that are intact; stimulation is applied to a different area of the sensory neural system that is not usually involved in hand sensation. It is then up to the user to perceive and learn the relationship between codification and modulation. Non-somatotopical stimulation is often referred to as sensory substitution and can provide a commercially viable solution [3]. However, due to the devices required, it often results in large components, such as vibrating pads being attached to the user's body. Common methods of providing non-somatotopical feedback involve the use of vibrotactile [8], [13], [14], electrotactile [6], [15], [16], or hybrid devices [3]. Alternatively, stimuli such as air or mechanical pressure can be applied [17], [18].

The process of gripping in the human body can be seen as a closed loop feedback system. When looking at the required control for gripping an object, the brain must send commands through the nervous system to muscles and tendons resulting

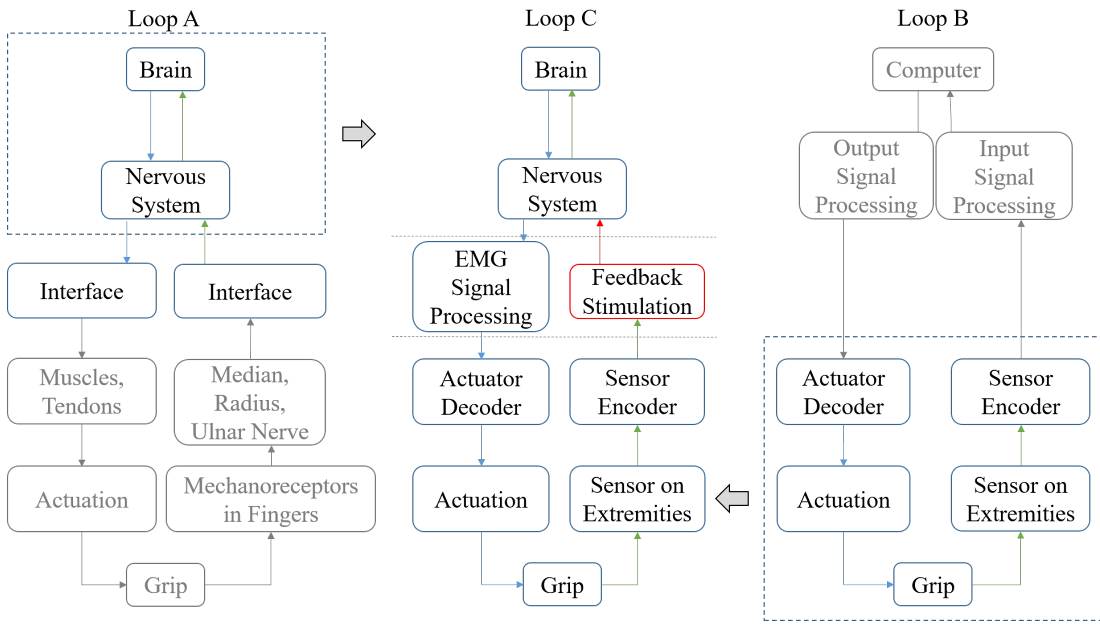


Fig. 1: Loop A: Human Body Closed Loop Control Diagram. Loop B: Robotic Hand Closed Loop Control Diagram. Loop C: Proposed Closed Loop Feedback Control

in actuation whilst simultaneously receiving information from neurons such as mechanoreceptors in the skin (as shown in Loop A, Figure 1). The brain acts as a central unit, receiving information and making predictions from multiple sources [11]. Missing connections in the loop occur when an amputation is performed [7]. In contrast, a robotic gripping system is shown in Loop B. The two feedback loops are similar in that commands are sent to actuators by a central processor and sensor information from the actuation is received and interpreted. In a robotic system, these actuators and sensors can be a number of solutions. In a human system, the actuators are muscles and tendons, and the sensors are mechanoreceptors and other neurons in the hand and fingers.

The missing connections caused by amputation in the human loop can be replaced by sections of the robotic loop (Figure 1). This will require interpretation of brain signals resulting in actuation of a prosthetic and the sensing of the physical environment. The sensor information must be fed back into the human system to complete the loop, either by introducing signals directly to the brain or through the nervous system. This feedback stimulation and interface into the human body is the focus of this research. This paper aims to characterize audio modulation as a means of transmitting the feedback information to the brain through sound.

The common aim of feedback methods is to maximize information transfer by providing multiple channels that the user can successfully interpret. Though, this needs to be applied cautiously as studies have found that the interpretation of a complex feedback signal can instead hinder the user's experience and increase the time taken to perform a gripping task. This inhibits the use of the prosthetic in daily life [6], [19] and can lead to abandonment [7].

Current audio modulation techniques have typically involved mixing two channels of information through a high and low frequency [20], [21], as well as modulation by frequency and amplitude (loudness) [22]. However, the level of understanding by these methods has not been rigorously characterized. Further understanding the parameters of audio feedback can allow for better, targeted codification of sensory information. In addition, concerns over its use in daily life were raised [23]. The ears were expected to be overloaded with sensation. The degree to which this is the case is yet to be determined. This paper contributes a method to systematically investigate timing and sensitivity parameters, as well as the learning rate, of participants engaged in motor tasks whilst responding to feedback provided via audio modulation. The premise of this paper is to capture the ideal case, where subjects are concentrating 100% on the feedback method. Bone conduction headphones are used to transfer the audio information to the ears without blocking them from hearing ambient sounds.

II. Proposed Method

The feedback experience of the user must be able to be characterized to ensure sensor information can be successfully coded, modulated, and understood. This was achieved by a series of multi-channel experiments. The results observed from the investigation can help develop meaningful multi-channel feedback methods for prosthetics, as well as human-machine interface applications.

1) Audio Feedback Characteristics: Audio feedback has a series of characteristics that can be exploited to modulate information (Table I). These are; Amplitude (loudness), Frequency (Pitch), and Beat Frequency (Observed resulting beat from

TABLE I: Experiment Channels and Stimulus Range

Exp	X Map	Range	Y Map	Range
A	Frequency	300-3400 Hz	Amplitude	50-65 dB
B	Frequency	300-1800 Hz	Frequency 2	1800-3400 Hz
C	Frequency	300-3400 Hz	Beat Frequency	0-15 Hz

two closely matching frequencies). Frequency modulation was used for comparison with successful trials achieved by Gonzalez et al. [21], [20]. In those studies, the frequency was in the form of musical notes ranging from a low C to a high C for a violin (high pitch instrument) and a cello (low pitch instrument). Frequency modulation in this set of experiments was on the range from 300 Hz to 3400 Hz. This range of frequency is used for telephone lines as it can be clearly heard by most individuals and it maximizes information transfer over a relatively small, limited bandwidth. Amplitude was selected due to the natural ability to detect loud and soft, such as in conversation. The loudness range used was between 50 dB (a whisper) and 65 dB (a typical conversation). Beat frequency was inspired by echo location found throughout nature, and is achieved by playing two closely matching audio frequencies. A combination of these modes creates the audio feedback, where one mode (channel) changes along the X axis, and the other along the Y axis.

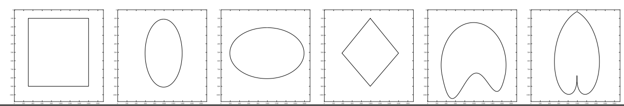
2) Coordinate Feedback Method: The sound "trajectory" that is played to the subject is created by following a path in both the X and Y dimensions. This is mapped onto the modulation output. The trajectories were calculated in MATLAB, which were designed to be followed in this 2-D space with constant speed. A series of six trajectories (Table II) were generated, each consisting of 2500 equally spaced points. A computer program, written in "Processing", took the coordinates from the generated trajectory and played the corresponding sound with respect to time. Each channel was linearly mapped onto the X or Y axis as shown in Table I. The modulation was updated at a frequency of 100 Hz. Thus, each experimental trial took 25 seconds. For each experiment, the subject was given a mouse and a computer screen and was tasked with drawing the trajectory that they heard. The mouse X-Y location was recorded with respect to time to investigate the subjects "perception" of magnitude. The aim of this experiment was to quantitatively characterize the quality, and latency, intrinsic to multi-channel audio feedback.

A. Subjects

The subjects were 8 healthy individuals, with no known hearing problems. Informed consent was obtained from each subject before performing the trials. This project was deemed to be low risk, and consequently did not require approval by the University's Human Ethics Committee. The researcher(s) named in this document are responsible for the ethical conduct of this research. The subjects hearing was protected by ensuring the sound from the headphones could not exceed 65 dB. This level of noise is consistent with a normal conversation and will not cause hearing damage to the subject.

TABLE II: Experiment Paths and Reasoning

Path	Reasoning
Rectangle	Used as control. Single channel changing at a time due to horizontal and vertical lines
Circle	Constant smooth change of both channels. Changing channel velocity
Ellipse	Skewed constant change of both channels.
Diamond	Linear change in both channels. Constant velocity along path
Bean	Further test of understanding of sound changes
Heart	Sudden change in direction followed by smooth travel along constantly changing velocity path.



B. Experimental Setup and Protocol

The subject sat in front of a computer with a computer mouse; they wore a set of headphones, which the "Processing" sound program played through. Before the test began, the subject was free to move the mouse to become familiar to how each of the channels changed with respect to the subjects movements. Once they were ready, the subjects were instructed that they could start a test by clicking the mouse at a specific location. They would then draw the trajectory which they heard. For example, in Experiment A, an increase in frequency would require them to move the mouse in the positive X direction, and increasing loudness required them to move in the positive Y direction. Each subject was exposed to three trials of the six distinct trajectories in a randomized order to prevent learning bias. This is used to give some insight as to the learning curve for each modulation technique. Each set of experiments took approximately 1 hour.

C. Sound Program

The starting coordinate displayed in the user interface (Figure 2) shows where the path begins. Cursor motion is shown to the user by a trail of dots. The trail length indicates the speed of the mouse movements. As the input sound changed with respect to time, the subject moved the mouse to represent how the sound varied. The program captures the cursor motion at 100 Hz, which captures the subjects perception of the trajectory.

D. Measurement Methods

The data analysis is based on mathematical correlation methods between the commanded trajectories, and subjects response paths, which reflect their perception of the modulation technique. Thus, the temporal trajectories in X and Y for setpoint and feedback can be examined simultaneously, as well as independently. This gives an insight as to the capability of the subject to simultaneously understand two channels of stimulus through their ears.

The captured data was processed to analyze parameters of the feedback channel, such as time delay and magnitude correlations between input and output. The data was first separated

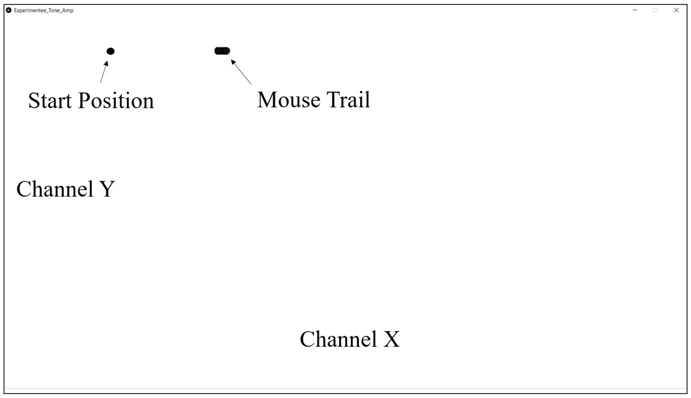


Fig. 2: Screenshot of Display Window

into the X and Y channels to be analyzed independently. All data were normalized such that their magnitude between their min and max values mapped between 0 and 1. The time delay was found by performing a cross correlation between the input path and the subject response. The input path was first clipped by 550 samples at the beginning and end to minimise any starting or finishing bias. The cross correlation result gives the required number of samples shift as to when the input best fits the output; this gives an indication as to the mean time delay throughout the trial.

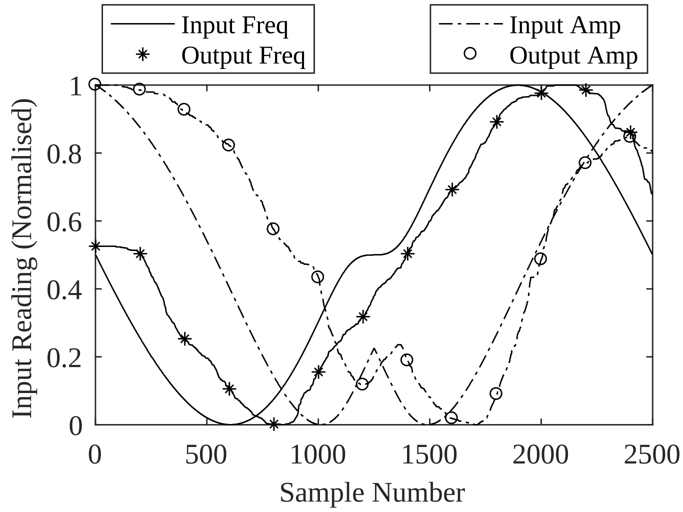
Once the time delay was found, the mean squared error of the input and shifted response was calculated. The shifted mean squared error indicates how well the response fits the input, giving insight into the sensitivity of the subject to the channels of the feedback.

III. Results

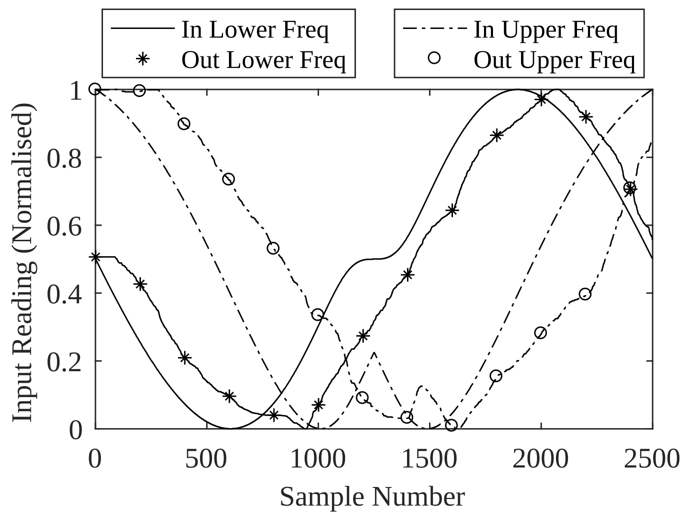
The subjects were able to understand the experimental protocol, and correctly use the sound feedback and computer mouse system. The mapping of the channels was largely followed correctly. Two out of 144 beat frequency modulation trials showed correct, but inverse responses, indicating one subject got confused as to the directionality of the channel mappings. The mean of the closest 17 trials per subject (out of a possible 18) was used to account for any outliers in the trials due to misinterpretation of the system or a singular, generally poor performance.

A. *Frequency and Amplitude*

Frequency and amplitude were anticipated to be the most easy for the subjects to conceptualize. An exemplary output, and associated feedback, for a “heart-shaped” trajectory is shown in Figure 3a. It is found that the average time delay is 1010 ms for the frequency channel and 1082 ms for the amplitude channel, which are comparable. This time delay captures the cognitive load and delay for movement of the mouse. The average mean squared error where the graphs correlated most highly represents how accurate the subject followed the changes in sound. The average shifted mean squared value for amplitude was 0.0829 and frequency was 0.0326, or 8% and 3% respectively.



(a)



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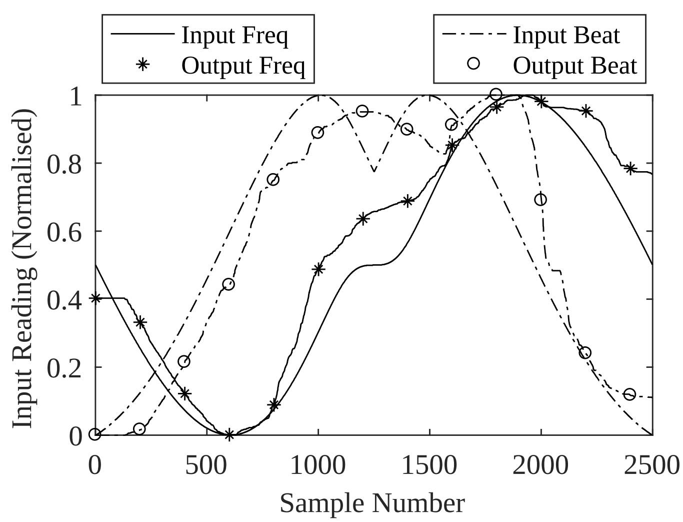

(c)

Fig. 3: Input and Output Response Comparison

TABLE III: Frequency and Amplitude Results

Subject	Av. Frequency Time Delay	Av. Amplitude Time Delay	Frequency Mean Squared Error	Amplitude Mean Squared Error
1	980ms	1545ms	0.0169	0.0324
2	475ms	548ms	0.4723*	0.0619*
3	1365ms	648ms	0.0520	0.0749
4	416ms	651ms	0.0331	0.0900
5	1009ms	1113ms	0.0293	0.1317
6	779ms	905ms	0.0298	0.1017
7	318ms	369ms	0.2384*	0.1092*
8	1508ms	1634ms	0.0346	0.0666
Mean	1010ms	1082ms	0.0326	0.0829

TABLE IV: Two Frequency Results

Subject	Av. Lower Frequency Time Delay	Av. Upper Frequency Time Delay	Lower Frequency Mean Squared Error	Upper Frequency Mean Squared Error
1	1562ms	1154ms	0.1877	0.0494
2	714ms	819ms	0.4206*	0.7247*
3	-725ms	3095ms	0.1518	0.5594
4	884ms	1250ms	0.1085	0.0367
5	1389ms	1314ms	0.2872	0.0328
6	1538ms	1391ms	0.0565	0.0335
7	-1127ms	1953ms	0.2371	0.2125
8	1918ms	1979ms	0.0842	0.0660
Overall	1094ms	1697ms	0.1460	0.1296

B. Two Frequencies

The subjects indicated that the two frequency channel feedback was difficult to interpret at first, however, the modulation was gradually understood. They reported that it was difficult to focus on them simultaneously. The lower frequency average time delay was 1094 ms with a mean squared error of 0.1460. The upper frequency average time delay was 1697 ms with a mean squared error of 0.1296. The higher mean squared error value indicates a less accurate response. Subject two had a notably bad performance using two frequency modulation, highlighting the difficulty observed. However, subject 5 became very proficient at the third trial, easily detecting both channels. This suggests that with training, other subjects may also become accustomed. Despite the trial being reported as difficult, the fedback trajectories were of a high accuracy.

C. Frequency and Beat Frequency

The frequency and beat frequency channels were readily understood by all subjects, with a low mean time delay of 522 ms and 602 ms for the frequency and beat modulation respectively. The mean squared error was found to be 0.0406 for the frequency modulation and 0.0658 for the beat modulation.

TABLE V: Frequency and Beat Results

Subject	Av. Frequency Time Delay	Av. Beat Time Delay	Frequency Mean Squared Error	Beat Mean Squared Error
1	574ms	878ms	0.0144	0.0339
2	1315ms	1395ms	0.3912*	0.4255*
3	1154ms	595ms	0.0595	0.0889
4	121ms	189ms	0.0327	0.0591
5	835ms	768ms	0.0386	0.0649
6	508ms	1136ms	0.0288	0.0474
7	37ms	595ms	0.1955	0.2434
8	-60ms	44ms	0.0698	0.1008
Overall	522ms	602ms	0.0406	0.0658

IV. Discussion

A. Feedback Methods

All three of the 2-Channel modulation methods were found to be suitable for providing feedback to the subject. It improved with training, which was observed as a reduction in mean delays and mean squared error (In both the X and Y dimensions). This indicates that the user could accurately understand, decode, and perform an action based on the feedback. Subjects reported that the two frequency modulation was difficult to understand at first (which could be attributed to the reduced range and overlap with the previous modulation technique). However, some subjects (6 and 8) were very successful in following this modulation scheme. This suggests that different users may have a preference for, or have better capability with, different schemes.

B. Learning Curve

There was an observed learning curve associated with understanding how the channels changed and relating this change in observed sound to a movement in the mouse position. This is supported by the increase in accuracy and reduction in time delay from Trial 1 through to Trial 3 by each subject. Subject 1 saw a significant decrease in the average mean squared error, with a p value of 0.004.

C. Cognitive Load

A stall in the observed increased performance can be linked to the cognitive loading of the feedback. Comments made by some subjects include feeling tired after the series of experiments. In particular, due to the two frequency modes which was reported to be difficult to comprehend and required focus to achieve the result.

The cognitive load can be seen in Figures 3a, 3b, 3c through the distribution of points along the path. The input was created with equal spacing between points, and constant speed motion along the path. The Figures show the output response has varying speeds, and the speed decreases where there are abrupt changes in trajectory. This suggests that the subject slowed down to focus on the sound. However, this is not foreseen as a major obstacle, as an amputee typically applies a high cognitive load to perform gripping and grasping (presently visual), which is significantly harder without this feedback.

D. Time Delay

There was an expected time delay from the time the sound played to the observed change in mouse position. The observed delay varied throughout each trial, and between subjects. The time delay must be accounted for in any application, such as sensory feedback for a prosthetic limb. A grabbing and lifting action with no impairment typically takes less than 100 ms from the first contact [24] and Gonzalez et al. [20] found the gripping action in their study increased to between 10 and 20 seconds. It is hoped that through better targeted feedback, the observed action time will be significantly reduced. The time delay observed in this study is the time taken from the subject hearing the sound, registering the change, and hence moving the mouse. Despite this delay, it is expected the increased action time will be useful for some amputees where reliance on visual feedback is no longer practical, and sensory substitution becomes favourable.

V. Conclusion

There are opportunities to further investigate how sensitive raw data can be distilled and interpreted into a coded feedback method such that the user can understand. Developed sensor devices can achieve high sensitivity, however, sensory feedback methods can transfer only some of this information. Challenges identified include applying feedback to the user that does not increase task duration. Dual-Channel Audio feedback presents a non-invasive method of providing this sensory feedback, however, the subject specific time delay must be considered. Frequency and Beat modulation was found to be successful with an average mean squared error of 0.0406 and time delay of 522ms for the Frequency channel, and 0.0658 for the beat frequency channel, with a time delay of 602ms. The methodology proved a successful method for measuring the response to each channel, and subjects were able to use and understand the system, as indicated by the low mean squared error results.

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