Center of Sensory Motor Interaction Department of Health Science and Technology Faculty of Medicine University of Aalborg

# Assessment of substitutive vibrotactile feedback for performing object manipulation task with prosthetics

#### Internship Report, by

Noud van Herpen s1351567 Mechanical Engineering, MS3

1<sup>st</sup> April - 29<sup>th</sup> June 2018



Faculty of Engineering Technology, University of Twente, The Netherlands Supervisor: Prof. Dr. Ir. André de Boer



Center for Sensory-Motor Interaction, University of Aalborg, Denmark Supervisor: Dr. Strahinja Dosen This report is a result of the activities undertaken during a three-month internship at the Sensori-Motor Interaction research group of Health Science & Technology at Aalborg University in Aalborg, Denmark. The internship is a part of the Master's programme of Mechanical Engineering at the University of Twente. The goal of the internship is to obtain some experience in the working field, out of the lecture halls. Therefore, the internship provides a general idea of the activities in a professional environment for an engineer. In this case, software programming, experimental methods (including human subjects) and scientific reporting were the main activities.

Since the internship was carried out internationally, in Aalborg, Denmark to be precise, not only educational & professional aspects came to light, but also cultural aspects.

### Summary

Amputees and other prosthetics users do not possess over the ability to perceive touch anymore. Implementing a feedback method that resembles the sense of touching could open up many opportunities for the user, such as regaining the ability to comfortably grasp a cup of water without breaking the cup. Simple object manipulation tasks become much more difficult when this sensory information (touch) is absent. Using a vibrating node to communicate exerted force (vibrotactile feedback), could serve as a substitutive sensory feedback method that could allow patients to perform these tasks with more ease and comfort.

To examine the usefulness of vibrotactile feedback, an application was developed that uses a haptic robot and 3D display. With this application, trials can be ran during which a subject needs to press on a virtual box with the end-effector of the haptic device and drag it to avoid crashing into incoming obstacles. The virtual box can also be broken by pressing to hard on it. This way, the subject needs to estimate and maintain the force exerted on the virtual object. The box shows deformation upon pressure.

Vibrotactile feedback is compared against scenarios where haptic force feedback is present and absent. It was found that supplying vibrotactile feedback does not significantly improve performance of the task compared to the scenario where only visual feedback (the deformation of the box) was supplied. Haptic force feedback does aid in completing the task, which was expected. For all feedback methods, training effects were observed. The performance of the last trial with each feedback method showed higher performance than the first trial the feedback method was supplied.

To be fully conclusive about whether vibrotactile feedback serves as a useful feedback method in every day grasping and dragging tasks, more subjects & trials are needed.

# Contents

1.	Intr	oduction	5
2.	Prol	blem Statement	6
	2.1	Background	6
	2.2	Literature	6
		2.2.1 Continuous Feedback	6
		2.2.2 Discrete Feedback	7
		2.2.3 Visual & Auditory feedback	8
	2.3	Research Question	8
3.	Met	hod	9
	3.1	Task description	9
	3.2	Materials	9
		3.2.1 Haptic Device	10
		3.2.2 3D Display & Kit	11
		3.2.3 Haptic Feedback Evaluation Kit	11
	3.3	Feedback Methods	12
		3.3.1 Haptic Force Feedback	12
		3.3.2 Disabling Haptic Feedback	14
		3.3.3 Visual Feedback	15
		3.3.4 Vibrotactile Feedback	15
	3.4	Application	15
		3.4.1 Configuration File	16
		3.4.2 The Game	16
		3.4.3 Data files	17
	35	Subjects	17
	3.6	Fxperimental Design	18
	5.0	3.6.1 Training & Instruction	10
		3.6.2 Experiment	10
	27		10
	5.7	Analysis	10
4.	Rest	ults	20
5.	Disc	cussion	21
6.	Con	clusion	22
7.	7. Recommendations		
8	Ack	nowledgements	22
Ар	Appendix A Urganisation structure		
Appendix B Reflection			25

# 1. Introduction

With the developments of prostheses, upper-limb amputees have regained the ability to do everyday activities like grabbing an object or pouring a cup of tea. One can imagine, that with the loss of touch, it can be very hard to perform these tasks. One well-known struggle for prosthesis users is grasping an egg, since estimating the force on the egg is critical to it cracking or not. This troublesome estimation process is mostly a result of the lack of information supplied to the user. In order to achieve better estimations more quickly, the user must be aided with more than just vision and hearing cues. Another way to phrase it: More information is needed to close the human motor control loop.

Besides visual and auditory information feedback, from the prosthesis to the user, it is possible to supply somatic information. Somatic information includes touch, proprioception, temperature and vibration information. To improve performance of the daily tasks as described above, touch (or tactile) information could offer significant benefits when fed back to the user. This can be done invasively (by interfacing directly to physiologically relevant neural structures in the peripheral nervous system or the CNS) or non-invasively. For the latter, one could think of providing feedback to intact sensory systems (e.g., vibration or poking on the residual limb, chest, etc.). Given that the background study here is mechanical engineering, and not medicine or surgery, the scope of this internship will be within the non-invasive methods range only.

When it comes to non-invasive tactile feedback, there is still a lot to discover. This stems from the requirements that a prosthesis and accompanying feedback & actuation methods have to meet. The system (prosthesis with accompanying feedback and actuation methods) must feel natural to the user. This could mean a lot of things, of course, and is therefore one of the reasons that even today, prosthetic rejection rates are estimated to be as high as 40%. Therefore, the main question is: How could the somatic information be fed back to the user in the most optimal way to reduce rejection rates and improve task performance?

The Center for Sensory-Motor Interaction (SMI) at Aalborg University (AAU) aims to develop new diagnostic and therapeutic methods in the areas of pain, motor control, and rehabilitation. In this case, SMI wishes to develop an experimental setup which can be used to investigate different aspects of somatic information feedback and prosthetics control performance. That is where this internship comes in. I was asked to develop an application that allows researchers to set up experiments within this scientific field. Moreover, the application could be used for educational purposes, like projects (which is synonymous with the Aalborg University).

# 2. Problem Statement

# 2.1 Background

The loss of a limb is a tragic event that comes with the loss of some vital abilities, like grasping or feeling touch. Artificial limbs, or prosthetics, allow amputees to regain some of these abilities, with increasing performance thanks to decades of research and development. However, it is estimated that still, about 40% [1] of the users reject their prosthesis with the main reason being that prosthetics do not offer the tactile sensation that the residual stump does [2]. Therefore, the next step in prosthetics development is to supply the user with sensory feedback for improved embodiment of the prosthesis. This way, the user regains the ability to feel a resembling substitute of touch again, and subsequently, use this tactile sensory feedback to actuate the prosthesis with more accuracy and precision.

# 2.2 Literature

It is still relatively unknown how this feedback can be supplied in an intuitive, efficient, and useful manner. There are many ways, as is depicted in the overview shown in Figure 1.



Figure 1: Mind map for feedback methods [11]

The available equipment during the internship allows to evaluate feedback methods from the vibration, force-feedback & visual paradigms. The latter two are not necessarily sensory feedback methods, but it has been shown that these two play a vital role in the execution of everyday grasping tasks [11]. Naturally, when grabbing something, the person relies on several cues that aid in estimating (among others) position, orientation and applied force on an object.

Besides the method modalities (vibration, force or visual), it is also important to analyse the way in which feedback information is supplied to the user. This can be done either in continuous fashion or by supplying information in a discrete manner.

#### 2.2.1 Continuous Feedback

A relatively simple way of translating tactile sensory information to the user is by using a vibrating node, placed on intact skin. This method is categorised under vibrotactile sensory substitution feedback. This vibration can be modulated in several ways to maximise the effectiveness of the feedback method.

Stepp et al. [13] assessed amplitude versus pulse train frequency (PTF) modulated feedback. Amplitude modulated feedback means that the vibration amplitude is proportional to the force exerted by the prosthesis on a surface. For PTF modulated feedback the repetition of a brief signal with uniform frequency and amplitude is more rapid when the force exerted is higher. It was concluded that amplitude modulated feedback provides superior feedback for object manipulation.

Rosenbau-Chau et al. [5] used a feedback system that had three stages of force; low, medium and high; represented by differing pulse frequencies and strengths. The effectiveness of sinusoidal, saw-tooth and square vibrational waves on amputees with upper limb prosthetic devices was examined and sinusoidal waveform performed the best.

#### 2.2.2 Discrete Feedback

However, there are some publications that argue that the human body acts on, in fact, discrete feedback information. In order to understand this, it is necessary to look into the physiological aspects of human touch sensation.

#### **Physiology of Sensing**

Figure 2 shows several things. On the right side, a cross-sectional view of a fingertip skin is shown. On the left, one can see the receptive fields of Type I receptors at the top, and Type II at the bottom. Receptive fields are the areas that one neuron can perceive stimuli from. In the middle, the discharge pattern of the receptors can be seen, followed by the density distribution on the right side of the table.



Figure 2: a) The receptive fields, pulse discharge pattern and density distribution of the mechanoreceptors. b) Schematic depiction of the cross-sections a fingertip highlighting the position & shape of the mechanoreceptors.

There are approximately 17,000 mechanoreceptor nerve endings in the glabrous (hairless) skin of the human hand, with a disproportionate number located at the fingertips (Johansson & Vallbo, 1979). The nerve endings are almost evenly split between two categories: slow acting (SA) and fast acting (FA)[10]. SA units respond to a step indentation of the skin with a constant discharge. This means that as an object is pushed and held against the skin, SA units will fire continuously. FA units respond only to the onset and removal of the stimulus. As such, they are effective at detecting high frequency vibrations (greater than 20 Hz), where an object is repeatedly pushed against and removed from the skin [4]. The nerve endings can be subdivided into type I and type II units. Type I units (fast adapting type I, or FA I, and slow adapting type I, or SA I) have small, well-defined fields of sensitivity, whereas type II units (fast adapting type II, or FA II, and slow adapting type II, or SA II) have larger fields with ill-defined borders. FA I units are sometimes referred to as rapid adapting (RA) units. Type I units have uniform sensitivity throughout their fields of sensitivity. They are also very sensitive to edge indentations of the skin and disproportionately present in the fingertips, which aids in object manipulation. When moving an object around in the hands, the fingertips are the part of the hand that is primarily used to grasp the object. This makes type I units very important to the task of object manipulation. Type II units have a much higher sensitivity to vibration than type I units. Type II units are defined by a single point of maximum sensitivity, with gradually reduced sensitivity further away from that

point. Unlike the type I units, type II units are relatively evenly distributed throughout the hand. Furthermore, their field of sensitivity is very large, often covering an entire finger. FA I fibres react most strongly to vibrations that occur at a frequency of 10 to 100 Hz [3]. According to Gescheider et al. [9], SA II and FA II fibres both have peak sensitivity to frequencies of about 15 to 400 Hz. However, they found that SA II units have a much lower sensitivity to vibration amplitude than FA II units. Lastly, SA I units are most sensitive to frequencies between 0.4 Hz and over 100 Hz[3], with a sensitivity similar to SA II fibres. As a result, the human hand responds well to vibrations that occur in a frequency range from about 0.4 Hz to 400 Hz.

An alternative to the previously mentioned continuous methods is the DESC model, which stands for Discrete Event-driven Sensory feedback Control. This model is based on the physiology of touch sensors in the human skin. In short, the DESC model postulates that human motor tasks are organised in phases delimited by temporal signals that are produced at the transition between two states. For instance, when contact is made with an object, the FA receptors will produce a signal that marks the next stage of the motor task: grasping. It is hypothesised that these discrete, event-driven signals aid the user in performing tasks in human motor control [8].

Cipriani et al. [6] explored the applicability of DESC for control by designing a task that can readily be learned and mastered under visual control, namely, lifting an object with a robot hand [7]. They concluded that the DESC model based feedback had been integrated with the sensorimotor control. It was also demonstrated that humans can integrate temporally discrete sensory feedback while controlling an artificial hand.

#### 2.2.3 Visual & Auditory feedback

When applying pressure on an object, the object deforms, depending on the mechanical properties of said object. The effect of object deformation on the sensitivity to small changes in force has been investigated by

## 2.3 Research Question

It must be noted that this topic, on substitutive methods for haptic feedback, is entirely new at the Aalborg University. In the first place, I was asked to develop a program that can be used by researchers to do experiments on substitutive sensory feedback methods. Before this internship, no one had yet developed a platform like this. Therefore, development time takes a major part of the available 3 months time. To make sure the internship also includes a part for acquiring new scientific, academic skills, it was decided that during this internship, also some research had to be done. However, because of the development time, the continuous vs. discrete paradigm is placed outside the scope of this internship.

The goal of the internship is to find out which types of feedback can be useful as a substitute for the sensation of touch. The available feedback methods include haptic force feedback, vibrotactile feedback & visual feedback. Therefore, the research question reads:

What is the performance enhancing effect of continuous haptic force, vibrotactile & visual feedback in case of a simple everyday manipulation task?

### 3. Method

To answer the research question quantitatively, a simple & measurable manipulation task must be designed. During this task the user can be exposed to three feedback configurations:

- Haptic force + visual feedback
- Vibrotactile + visual feedback
- Visual feedback only

Every object shows some compliance, in reality. It would be unnecessary to investigate the role of visual feedback, since that is something that is naturally there.

### 3.1 Task description

As an example of a task that is simple, yet suitable for an experiment, inspiration is drawn from Stepp's research on vibrotactile substitutive feedback. During this task, the user was asked to press on a box, with enough force, and drag it towards a target without breaking it. In order to move the box, a threshold (which represents the force needed to overcome friction) had to be reached. This threshold is called  $F_{move}$  in this report. There was also a second threshold which would cause the box to break when it was exceeded, coined  $F_{break}$ .

For this research, a more interactive, dynamic task was desired. An important thing to highlight, is the cognitive task. Since it was reported that prosthetics users wish to perform simple tasks without paying excessive, the experiment task should take away the attention of the user from the dragable box. As a source of inspiration, an environment similar to the game Cubefield is made, where you have to dodge incoming objects. See Figure 3. This way, the user has to focus on the incoming objects instead of the dragable box.



Figure 3: Left side, a screenshot from the online game CubeField with the black triangle as the player's avatar. Right side, a screenshot from the developed application for this experiment with the blue box as the dragable box.

## 3.2 Materials

For Stepp's publication, a setup consisting of a 3D display combined with a haptic device was used. See Figure 4. Starting at the top, a 3D display is mounted to the top part of the frame. The subject looks down at a mirror that reflects the picture from the 3D screen. Under the frame, there is the haptic device. The subject holds the end-effector of the device and moves it to maneuver a small

sphere in the 3D virtual environment that is displayed on the screen. In this virtual environment, the manipulation task is shown. The user looks down so that it feels natural that the sphere is a representation of the end-effector position in the virtual environment.



Figure 4: Experimental setup used by Stepp for dragging experiments. A) A close-up of the end-effector. B) Schematic drawing of the dragging task.

A similar setup was made by professor Dosen before the start of this internship.

#### 3.2.1 Haptic Device

The word haptic, from the Greek: haptikos, means "pertaining to the sense of touch". A haptic device recreates the sense of touch by applying forces or motion to the user. This mechanical stimulation can be used to control virtual objects in a simulation. Haptic technology has made it possible to investigate how the human sense of touch works by allowing the creation of carefully controlled haptic virtual objects.

The device at hand is a Phantom Premium 1.5 High-Force model. It has 3 DOF, so torques and angular data can not be worked with. The Phantom can return interactive forces with the virtual environment, which will be very helpful during the experiments because the force exerted by the user on the virtual object must be compared to the force thresholds  $F_{move}$  and  $F_{break}$ .

To use the Phantom for the game, the XML-based programming language H3DApi is used. This language allows to:

- create the virtual environment (objects, playing field & text prompts)
- Provide properties of the virtual objects such as position, velocity, colour and surface stiffness.
- Record positions, velocities, reaction forces and time

H3DApi is responsible for calculating the haptic forces (reaction force, etc.). This calculation algorithm is called haptic rendering and will be discussed more in-depth in Section 3.3.1. Very sum-

marised: haptic rendering calculates the reaction force of a surface on the end-effector based on the position of the end-effector.

#### 3.2.2 3D Display & Kit

To produce the illusion of a 3D image, a 3D display and the Nvidia 3D Vision Kit are used. The principle of this technology is called Active Shutter 3D System. It works by only presenting the image intended for the left eye while blocking the right eye's view, then presenting the right-eye image while blocking the left eye, and repeating this so rapidly that the interruptions do not interfere with the perceived fusion of the two images into a single 3D image. See Figure 5. The left-eye image is from a slightly different perspective than the right-eye image, just like how humans can see 3 dimensions.



Figure 5: Principles of an Active Shutter 3D System.

#### 3.2.3 Haptic Feedback Evaluation Kit

To provide vibrotactile feedback to the user, the Haptic Feedback Evaluation Kit from Precision Microdrives is used, which is also shown in Figure 6. This external device is a combination of an Arduino chip and vibration node. The Arduino chip can interact with the developed application. The kit is capable of providing a wide range of predefined vibrations. For this experiment, the haptic kit will deliver a vibration that has an intensity proportional to the force exerted on the virtual object during the task. The intensity is dictated by the given voltage on the vibration motor. Since the Arduino chip can only enable (1) or disable (0) the full voltage, Pulse-Width Modulation (PWM) is used to communicate analog values with the chip.



Figure 6: The HEFK: Haptic Evaluation Feedback Kit from Precision Microdrives. The Arduino chip on the right side, is accompanied by the vibration node on the left side.

It might be quite confusing that this device is called the Haptic Kit, since in this study, the haptic feedback will be provided by the Phantom, and the vibration will be provided by the Haptic Kit. All these devices combined, and a computer, complete the experimental setup, which is shown in Figure 7.



Figure 7: Experimental setup with A) The haptic device, B) the 3D display, C) Nvidia 3D Vision Kit, D) Haptic Feedback Evaluation Kit, E) mirror and F) the frame supporting the display and mirror.

# 3.3 Feedback Methods

The three feedback methods mentioned in the problem definition are:

- Haptic Force Feedback
- Vibrotactile Feedback
- Visual Feedback

This subsection will further explain how each of these types of feedback will be applied to the manipulation task.

#### 3.3.1 Haptic Force Feedback

When using haptic force feedback, the haptic device applies a force to the user. As explained in SEC-TION, haptic force feedback is based on haptic rendering: the algorithm that calculates the magnitude and direction of the applied force by the device. Figure 8 shows a simple haptic rendering algorithm in the case of a rigid surface. Ideally, the avatar (the representation of the end-effector position in the virtual environment) will stay on the right side of the surface. However, since this is not an ideal world (I am terribly sorry), the haptic device will allow movement through the surface. Haptic rendering needs this distance to calculate the magnitude of the force, otherwise you would feel the same reaction force regardless of the exerted force. This simple algorithm is based on the spring equation (F = kx). An ideal haptic device, would have an infinite stiffness.



Figure 8: A basic linear-spring haptic rendering algorithm.

In H3DApi, this avatar is called the tracker position (TP). In other words, haptic feedback is based on the TP. Besides TP, H3DApi also uses the proxy and weighted proxy position (PP & WPP, respectively). Figure 9 shows an overview.



#### Virtual Position Representations

Figure 9: Overview of position representations in H3DApi. The blue box is the dragable, deformable box. The Proxy clings to the last surface it collided with. The Tracker is the H3DApi equivalent to the avatar from Figure 8. The Weighted Proxy has a weighting of 0.5 in this case, meaning it is exactly in the middle of the Tracker & Proxy. This weighting is always hardcoded in H3DApi, and by default 0.95

PP is used to detect collision with haptic objects in the virtual environment. These are objects that can be 'touched' by the user and give a reaction force when done so. PP represents the position of the ideal avatar. It is merely a representation and can not be used for custom haptic rendering algorithms.

WPP is a weighted average between TP & PP. By default, the weighting is set to .95 (on a scale from 0 to 1: completely dictated by TP & PP respectively). In the 3D environment rendered by H3DApi (graphically, this time, not haptic), a white sphere is shown to resemble the position of the end-effector. The position of this dot corresponds with the WPP, so technically, it is not completely the same as the end-effector position. When a surface is touched, the white sphere will slightly sink into the box. The WPP

has no function in haptic rendering.

It is important to know the difference between these position representations, because of two things:

- 1. In a scenario where haptic feedback is disabled, thus haptic rendering too, we need to translate the sunken distance into the box (of the TP) to a force manually. This resultant force needs to comply with the force the haptic device would record, because the force thresholds need to remain constant for all feedback configurations. Regardless of whether haptic feedback is enabled or disabled.
- 2. To display visual feedback as realistic as possible. By visual feedback, the object's geometric compliance is meant. The deformation of an object upon exerting a force is a visual cue that helps in estimating the exerted force. To model the compliance, we need to pick the right position representation in the virtual environment.

#### 3.3.2 Disabling Haptic Feedback

Focusing on the former, it was found that the specified stiffness in H3DApi, does not correspond with the actual stiffness from the haptic rendering algorithm (recall, F = kx). Figure 10 shows the relation between force and TP for a specified stiffness of 2000 N/m. Instead of a slope of 2000, the slope here is equal to 70 N/m. The meaning of the slope is the haptic rendering stiffness.



Figure 10: Measured force on various depths. A line can be interpolated. The slope of this line can be interpreted as the stiffness of the haptic rendering algorithm.

But maybe 2000 N/m is just too large of a value for the haptics device to handle. Right? To find out if that is the case, the haptic rendering stiffnesses are plotted for several specified stiffnesses. This is shown in Figure 11. It can be seen that the maximum rendering stiffness is around 1000 N/m. Beyond that, the stiffness delivered by the haptics device does not increase any further.

To get rid of the whole specified vs actual rendering stiffness, it was decided to move to relative values. In the end, haptic rendering is desired to be as ideal as possible, in this case, with a maximum stiffness. This shifts Figure 11 to Figure 12.

Recall the scenario without haptic feedback. In this scenario, the force must be calculated manually. Now that we know that the maximum rendering stiffness is equal to 70, the force can easily be





Figure 11: Interpolation of haptic rendering stiffnesses plotted for the specified stiffness in H3DApi when absolute stiffness values are used

Figure 12: Interpolation of haptic rendering stiffnesses plotted for the specified stiffness in H3DApi when relative stiffness values are used

calculated with  $F = 70 \cdot k_{relative} \cdot x$ , with x being the sunken depth into the box. This force can be compared against the force threshold to determine whether the box can move or is broken.

#### 3.3.3 Visual Feedback

The goal is to provide compliance to the object, such that the user can estimate the exerted force. However, the combination of haptic rendering and a compliant surface is an ongoing topic in the scientific community. Because implementation of visual compliance came at a late stage during this internship, it was decided to make a simplified compliance algorithm.

In case of haptic force feedback, the top surface of the box will follow the WPP. When haptic force feedback is not enabled, the TP will be dictating the box's height.

#### 3.3.4 Vibrotactile Feedback

Vibrotactile feedback is supported by the Haptic Feedback Evaluation Kit from Precision Microdrives. During pre-testing, it was found that the intensity does not scale linearly. From a certain value, the intensity plateaued. This made it more difficult for the subject to clearly identify the  $F_{break}$  threshold. To circumvent this, the intensity range was changed from 0 to max voltage, to 17% to 50% voltage. 17% is chosen as the minimum, because upon contact, it is desired to have some feedback you can actually feel. From 50% onward, the intensity stops growing linearly and plateaus. See Figure 13. Moreover, during pre testing, it was confirmed by all subjects that this range of vibration intensity provides a perceivable change in vibration intensity between  $F_{move} \& F_{break}$ .

## 3.4 Application

Ultimately, the application that was developed during this internship consists of the following parts:

- Configuration file
- Game code
- Data files

This section will not cover the development of the game, but shortly introduce some details that are important to the experimental design.



Figure 13: Selection from voltage range that scales roughly linearly.

#### 3.4.1 Configuration File

The configuration file is a very simple Comma Separated Value (CSV) file that contains parameters like:

- Mechanical properties of the dragable box
- Force thresholds (*F<sub>move</sub>* & *F<sub>break</sub>*)
- Velocity of incoming obstacles
- Firing rate of incoming obstacles
- Duration of the experiment
- Which feedback modes to enable

With this approach, it is very easy for others to modify these parameters to their liking. To promote usage of the application by other scientists, two guides were written. One for usage (user guide), and one for modification (developer guide).

#### 3.4.2 The Game

During one game, the user is guided by a haptic spring force that points at the initiation position. Once in position, the proxy position will be locked using a haptic magnetic force until a countdown of 3 seconds ends. 3 Seconds later, the first obstacles are being fired at the fixed rate and speed specified in the configuration file. The user must approach the dragable box, establish a force on the box that lies between the thresholds  $F_{move}$  and  $F_{break}$ , and dodge the incoming obstacles until the specified time runs out. In this case, the time limit was 60 seconds.

In the event of collision with an incoming obstacle or a 'break' because the force exerted exceeds the  $F_{break}$  threshold, the dragable box becomes invulnerable for a short 3 seconds. During this period, it is not possible to 'get fouled' for collision nor breaking the box. Also, no points will be added to the total score during invulnerability. The box turns orange to indicate invulnerability.

The positioning of the incoming obstacles at the horizon of the playing field is completely randomised. It is expected that during the experiment, sufficient data is gathered to average out possible bias towards lucky positioning patterns. Moreover, learning effects are countered by random positioning.

When pushing on the box, it can be seen that the proxy sinks in the box. At one point during development,  $F_{move}$  was set such, that the proxy did not fully sink in before exceeding the threshold.

It was found that testers exploited the visual cue from the half-sunken proxy. They were controlling the force on the box by looking at the position of the proxy. Therefore,  $F_{move}$  is required to have a corresponding fully-sunken proxy position.

Each time the game is played, one of the three feedback configurations can be used.

Figure 14 shows a photo of professor Dosen playing the game.



Figure 14: Supervisor playing the game

#### 3.4.3 Data files

When a trial is finished, a csv file will be saved in a sub folder. This csv file can be imported by Matlab, Python or even Microsoft Excel. Personally I prefer to stick with python, because that is how the data was ordered, therefore with python, the most logical data layout will be obtained.

A separate python file was created that creates one big Pandas DataFrame of all the trials. That complete DataFrame was exported to csv to have all experiment data in one place, instead of scattered all over subfolders. Also, this file can be used as a module that has built-in functions to plot specific graphs.

## 3.5 Subjects

In total, seven subjects were willing to volunteer. All subjects were either students or PhD-candidates at AAU at the time of conducting the experiments. The individuals reported normal hand function, with no complaints related to their hands. Informed consent was obtained from all participants in compliance with the Declaration of Consent from the National Science Ethics Committee of Denmark.

# 3.6 Experimental Design

#### 3.6.1 Training & Instruction

All participants were introduced to the setup and the game by a brief introductory explanation. Subjects were informed about the purpose of the experiment, experimental setup, game mechanics (force threshold, invulnerability, work space) and feedback methods.

For the first 10 minutes, approximately, the subject was allowed to get accustomed to the game. During training, the force thresholds were altered, preventing subjects to exploit their knowledge on the force thresholds during measurements. First, force feedback was introduced without incoming objects. The subject identified the movement thresholds and purposely broke, and slipped from, the object. When the subject felt comfortable operating the haptic device, some incoming objects were added.

After that, only visual feedback was introduced. This mode required on average more training. The absence of force feedback was a surprise to most, even though they were informed about it.

When the subject was able to move the box, vibrotactile feedback was added. Because the vibration motors make a sound with frequency proportional to intensity, the subject could control the box by relying on this auditory signal. Since auditory feedback is not what is being investigated, the subject listened to some music through in-ear headphones. Each subject received a fresh pair of ear buds. The subject holds the vibration motor in their non-dominant hand, palms facing upward, with a moderate grip on the vibration node.

During pre testing, some inconsistencies among tests arised. These inconsistencies were reported and used to make instructions. These instructions lead to more consistent experiments. The inconsistencies & instructions arised were:

- Some pre test subjects were holding the end-effector differently than others. Therefore, during the experiment, subjects are told to hold the end-effector as close to the end as possible, between thumb (under), index & middle finger (on top).
- When slippage from the box occurred, some subject tried to regain control of the box by approaching it from the side, since that is the shortest path. However, due to the way the application was coded, this would lead to even more breaks. During the experiment, subjects were instructed to approach the box from the top whenever slippage occurred.

#### 3.6.2 Experiment

The experiment consists of 6 trials from every feedback configuration each. That means that in total 42 trials per subject are done. The order of the feedback configurations during these 42 trials were randomised. Each trial consists of 1 minute performing the task. The force thresholds were set to 0.6N & 1.6N for  $F_{move} \& F_{break}$  respectively. Objects were fired at 2Hz with a velocity of .06m/s.

# 3.7 Analysis

Performance variables used are number of crashes, breaks & slippages. Slippage is defined as the moment the tracker position goes out of the box volume while contact is had, but the applied force magnitude is smaller than  $F_{move}$ . See Figure 15.

The acquired data is obtained at a rate of 30Hz. The DataFrame contains:





- Trial settings (Feedback configuration, subject name, trial number, force thresholds, object firing rate)
- Event dictionaries. One dictionary contains information about every break, collision and slip from the object, complete with time stamp and location. Slippage was counted in post-processing from tacker position & force data.
- Total event counters. How many breaks, collisions and slips occurred in total during one trial? These columns contain that information. It could be deducted from the even dictionary, but that takes a lot of time.
- Recorded data. This includes time stamps, forces on the object, tracker position and velocity, dragable box position and velocity.
- Bullet pattern. Where was each incoming object placed on the horizon?

This gives a very complete data set that is ready for post-processing and contains a lot of valuable information.

### 4. Results

In total 126 trials were executed during which the dragable box was broken 359 times, crashed into another box 142 times and slipped from the object 286 times. Figure 16 shows the amount of breaks, collisions and slippages categorised per feedback configuration per trial. As can be seen, the amount of 'fatal' (breaks & collisions) events, is the lowest in case of haptic force feedback. Most subjects succeeded in not breaking the box with haptic force feedback, with a couple of outliers. For collisions, the median is consistent among all feedback configurations. Slippage occurs most in case of haptic force feedback, and the least with visual feedback only.



Figure 16: Boxplot of all 3 events, categorised per feedback type. Plot includes outliers, indicated with circles.

Figure 17 shows the effect of training. Each subject had 6 trials with each feedback configuration. From each attempt, the average among all subjects is plotted. It can be seen that haptic force feedback makes the most consecutive improvements over trials. Vibrotactile feedback starts out as the most challenging feedback configuration with the most events at the first trial. However, in the end, the training effects seem more apparent in vibrotactile feedback than visual feedback only.



Figure 17: Sum of events per trial, categorised per feedback type.

### 5. Discussion

Comparing the vibrotactile feedback paradigm to haptic force & only visual feedback, it can be seen that vibrotactile feedback does not prove itself as a significantly performance enhancing means of sensory substitution when used during a simple dragging task that requires precise force estimation.

Earlier studies [12] showed that changing the location of the applied vibration does not yield a significant increase in performance when compared to repeated training. Therefore, it is not expected that changing the site of the vibration node will significantly improve performance.

From Figure 16, it can be seen that the haptic force feedback method resulted in an abundant amount of slips. Although slippage is not a 'fatal' event, it shows that subjects had difficulties adjusting to the feedback method and did not feel natural.

When looking at training effects in a random order of feedback methods (which is thus not repeated), it can be seen that all feedback methods show improvement. The large difference in performance between the first and last trial of haptic force feedback shows that, even after introductory training, the subjects have learned a lot about not only the feedback method, but also on operating a haptic device and completing the game. None of the subjects had ever used a haptic robot before. The large improvement could be a result of insufficient training to begin with.

That subjects were new to the setup became especially clear when the subject slipped from the box. Some subjects reported that their first thought was to regain control of the box as quick as possible. Even after clear instruction to approach the box from the top, some could not resist the urge to take the shortest path: a sideways approach to the box.

Inspecting the vibrotactile feedback training line, the large spike at the  $5^{th}$  training immediately stands out. This spike is mainly caused by the performance of 2 subjects. While in the fourth trial, performance was exceptionally high, at the fifth trial performance was exceptionally low for these two subjects. A possible cause for this could be the randomisation of incoming obstacles.

When looking at the task that was designed, it could be argued that it is not an every day task to keep dragging an object for a minute long. Maintaining proper force on an object is important in grasping tasks, but with this task design, maintaining proper force might be overvalued.

## 6. Conclusion

This study shows that vibrotactile feedback does not provide an adequate substitutive sensory feedback method. With the designed experiment and available setup, it was shown that training, although only examined short-term, is of vital importance to the performance of the dragging task. It is not expected that applying the vibration elsewhere on the human body will result in better performance. Operating the haptic device was new for all subjects, meaning that the improvement over trials could be a result of insufficient training to begin with. More subjects are needed to average out outlying results that were caused by randomisation. To mimic a more realistic every day task, a different task might have to be designed.

# 7. Recommendations

Reported earlier by various sources [6], [10], additional event-discrete feedback signals could improve performance of the dragging task. With the current setup, it is possible to implement these event signals, such as an extra bump from the vibration node upon establishing contact, passing  $F_{move}$  or breaking the object. It could be worthwhile to investigate the effect of event-discrete feedback signals on performance for a simple manipulation task.

As discussed earlier, the sudden lapse of mean performance during the  $5^{th}$  vibrotactile feedback trial might be caused by a randomised object pattern. To verify this, it is recommended to reuse the same pattern (which is saved for each trial) and repeat trials with other subjects.

To be fully conclusive about whether vibrotactile feedback serves as a useful feedback method in every day grasping and dragging tasks, more subjects & trials are needed. It is recommended to at least have 20 subjects perform the experiment.

Regarding the programming of the application, it might be better to make the visual compliance more realistic. In this case, the box deformed uniformly. It would be more realistic if volume was preserved upon deformation.

# 8. Acknowledgements

I would like to express my gratitude towards my supervisor, Strahinja Dosen, who has been incredibly thoughtful on everything that was achieved during the three months at SMI in Aalborg, Denmark. It was a pleasure working with someone who is exceptionally motivated by & for science. Furthermore, I thank Jakob Lund Dideriksen for his advice on, among other things, experimental design. I wish him a successful journey towards his doctor's title. Other colleagues that I got to know from SMI were always available for advice, which I appreciate deeply.

But besides the professional contacts that I was able to establish, they cannot be left out: shout out to my friends at Nordjysk Handelskollegium for an amazing stay in Aalborg.

### References

- [1] Elaine A Biddiss and Tom T Chau. "Upper limb prosthesis use and abandonment: a survey of the last 25 years". In: *Prosthetics and orthotics international* 31.3 (2007), pp. 236–257.
- [2] Elaine Biddiss and Tom Chau. "Upper-limb prosthetics: critical factors in device abandonment". In: *American journal of physical medicine & rehabilitation* 86.12 (2007), pp. 977–987.
- [3] Stanley J Bolanowski Jr et al. "Four channels mediate the mechanical aspects of touch". In: *The Journal of the Acoustical society of America* 84.5 (1988), pp. 1680–1694.
- [4] Darwin G Caldwell, S Lawther, and Andrew Wardle. "Tactile perception and its application to the design of multi-modal cutaneous feedback systems". In: *Robotics and Automation, 1996. Proceedings., 1996 IEEE International Conference on.* Vol. 4. IEEE. 1996, pp. 3215–3221.
- [5] Teri Chou et al. "Development and Real World Use of a Vibratory Haptic Feedback System for Upper-Limb Prosthetic Users". In: (Aug. 2016), p. 1.
- [6] Christian Cipriani, Marco D'Alonzo, and Maria Chiara Carrozza. "A miniature vibrotactile sensory substitution device for multifingered hand prosthetics". In: *IEEE Transactions on Biomedical Engineering* 59.2 (2012), pp. 400–408.
- [7] Francesco Clemente et al. "Humans Can Integrate Augmented Reality Feedback in Their Sensorimotor Control of a Robotic Hand". In: PP (Oct. 2016), pp. 1–7.
- [8] J Randall Flanagan, Miles C Bowman, and Roland S Johansson. "Control strategies in object manipulation tasks". In: *Current opinion in neurobiology* 16.6 (2006), pp. 650–659.
- [9] George A Gescheider et al. "Vibrotactile forward masking: psychophysical evidence for a triplex theory of cutaneous mechanoreception". In: *The Journal of the Acoustical Society of America* 78.2 (1985), pp. 534–543.
- [10] Roland S. Johansson and Åke B. Vallbo. "Tactile sensory coding in the glabrous skin of the human hand". In: *Trends in Neurosciences* 6 (1983), pp. 27–32. ISSN: 0166-2236.
- [11] Benjamin Stephens-Fripp, Gursel Alici, and Rahim Mutlu. "A Review of Non-Invasive Sensory Feedback Methods for Transradial Prosthetic Hands". In: *IEEE Access* (2018).
- [12] Cara E Stepp and Yoky Matsuoka. "Object manipulation improvements due to single session training outweigh the differences among stimulation sites during vibrotactile feedback". In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 19.6 (2011), pp. 677–685.
- [13] Cara E Stepp and Yoky Matsuoka. "Vibrotactile sensory substitution for object manipulation: amplitude versus pulse train frequency modulation". In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 20.1 (2012), pp. 31–37.

# A Organisation structure

The Center for Sensory-Motor Interaction (SMI) at the Aalborg University (AAU) is part of the Health Science & Technology department at the Faculty of Medicine. Translational research in neuroscience and engineering is the primary focus of SMI. The aim is to develop new diagnostic and therapeutic methods in the areas of pain, motor control, and rehabilitation. SMI is an international research and training center with 50% of the staff coming from abroad, and the working language is English. The organisation fo SMI is visualised in the chart in Figure 18.



Figure 18: Organisation chart of SMI

More specifically, my supervisor works for the Integrative Neuroscience research group. Some of the ongoing projects are, among others:

- Tongue controlled robotics to aid patients that are paralysed from the neck down in performing every day activities such as picking up a cup of water and drinking it.
- REMAP project: To develop and implement novel assistive technologies for ALS patients by integrating state-of-the-art brain-computer interface (BCI) control with robotic assistive devices (exoskeleton arm and gloves) to regain/enhance patient's motor function for an improved physical performance.

The AAU is reknown for being the world leader in Problem-Based Learning (PBL), which is also thoroughly adopted by the University of Twente. The PBL model includes project work based on authentic problems, self-governed group work and collaboration. The PBL model assumes that students learn best when applying theory and research based knowledge in their work with an authentic problem. At the same time, the model supports students in the development of their communication and cooperation competences, and in acquiring the skills required when taking an analytical and result-oriented approach.

## **B** Reflection

First off, I had a great time in Denmark. This also holds for at the faculty. I was given a lot of freedom in the approach to this internship. Collaboration with professor Dosen was very close. We discussed nearly twice per week, every week. During these discussions I was pleasantly surprised how much thought and critical discussion was put in these meetings. Every meeting started with reporting the progress, showing the state of the software application, evolving into a brainstorm of directions we could take on, which proved very motivating throughout the whole process. Communication was very clear. There were no major misunderstandings.

The most educational part of this internship was during pre-testing. This phase was the last phase before we would conduct the experiments. Several PhD candidates at SMI were so kind to volunteer with the pre tests. They gave me a ton of useful insights in experimental design. Especially experiments with human subjects. That involves things that deal with minimising the use of exploits in the experiment, or fatigue problems that could arise, just to give a few examples. I was able to collect and process all of this information thanks to asking the right questions, having an eager attitude towards improvement and comprehensive documentation.

Contrary to projects and exams you do for your own degree, this internship made my contributions feel truly important. It was not just for those 5 EC on Osiris. This was also to enable others doing their research, and in their turn contribute to science with a publication. For that, the internship was a bit too short, but one colleague was very eager to analysing the full data set I was able to collect.

Socially, I felt included. From the neighbouring office, one colleague came in and picked me up for lunch with the other staff members. The atmosphere was very amicable at SMI.

Personally, I expected the internship to be more strict. Formal, maybe. But this was a research group at a University in a country that is very progressively minded. I liked it, and felt like a good fit to me. In the end, professor Dosen and Jakob Lund Dideriksen even expressed their desire that I would inform them about my plans after my studies.