6-2017

Investigation of Measured Cane Vibrations for Prediction of Blind Pedestrian Performance in Surface Preview Tasks

Aaron Dean
Western Michigan University, aaron.thomas.dean@gmail.com

INVESTIGATION OF MEASURED CANE VIBRATIONS FOR PREDICTION OF BLIND PEDESTRIAN PERFORMANCE IN SURFACE PREVIEW TASKS

by

Aaron T. Dean

A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science in Engineering (Mechanical)
Mechanical and Aerospace Engineering
Western Michigan University
June 2017

Thesis Committee:

Koorosh Naghshineh, Ph.D., Chair
Richard Meyer, Ph.D.
Dae Kim, Ph.D.
Robert Wall Emerson, Ph.D.

INVESTIGATION OF MEASURED CANE VIBRATIONS FOR PREDICTION OF BLIND PEDESTRIAN PERFORMANCE IN SURFACE PREVIEW TASKS

Aaron T. Dean, M.S.E.

Western Michigan University, 2017

The white cane is the primary navigation tool used by many blind pedestrians, but the basic design of the cane has not changed since the 1940s. A greater understanding of the factors affecting cane performance is essential in improving the design and performance of these canes. One aspect of performance is surface texture discrimination. A study is performed to determine the effect of cane rigidity and cane swipe speed on the ability of a user to select the rougher of two surfaces with different textures. Two methods are developed to select the rougher surface using only the measured cane vibration. The first method makes a selection using the change in frequency of high amplitude acceleration peaks caused by the interaction of the cane tip and the surface, the second method uses the overall amplitude of vibration to make a selection. Both methods correctly predict the rougher surface at the same rate as the participants in the study. This shows that changes in both frequency and amplitude may be important cues for texture discrimination. A pilot study is also performed to investigate the use of vibration cues for the detection of drop-offs in the walking surface.

ACKNOWLEDGEMENTS

I would first like to thank Dr. Koorosh Naghshineh for his ongoing guidance, support and advice throughout this project. I am grateful for the input and assistance of my committee, especially to Dr. Dae Kim and Dr. Robert Wall Emerson for their willingness to support interdisciplinary works like this one. I express my gratitude to Mike Konkel for assistance manufacturing the textured plates and to Blair LaCross for the hours of assistance in data collection and post processing. I am grateful to Pete Thannhauser for suggesting that I consider the spacing of the high amplitude vibration peaks, which led to the analysis methods developed here. Thanks to Mofareh Ghazwani and Brent Kostich for their encouragement along the way. Finally, I would like to thank my parents, Thom and Kathy, and my brother, Jacob, for the daily support and encouragement during this work.

Aaron T. Dean

TABLE OF CONTENTS

Table of Contents - continued

CHAPTER

Table of Contents - continued

CHAPTER

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

This chapter provides an introduction to the content of this thesis. An introduction to the white cane is provided in Section 1.1, followed by the motivation for this project in Section 1.2, then an overview of the rest of this work in Section 1.3.

1.1. The White Cane

The white cane is one of the principal tools used for navigation by individuals suffering from blindness or low vision. It is swept across the path of the individual in order to check for objects and obstructions, and can also be used to determine characteristics of the walking surface. Individual canes may differ in material, length, handle, and tip.

The ideal length of a white depends on the user's height. One common way of selecting the length of a cane for a user is to match its length to the vertical distance up from the ground to just above the sternum. This is called the sternum method [1]. The cane shaft is typically ½ inch in diameter, is sometimes tapered toward the end, and is often made from wood (usually poplar), aluminum, graphite, or fiberglass. Many canes are made from a single rigid shaft, although some canes are telescoping or foldable, to make them more convenient to transport. Cane handles often resemble a golf club grip, and may be made from rubber, foam or plastic. Figure 1.1 shows several different canes with a range of tips and handles. Figure 1.2 shows a folded travel cane and retracted telescoping cane.

Figure 1.1: (a) Rigid fiberglass cane with a glide tip, (b) foldable aluminum cane with a roller-ball tip, (c) poplar cane with a pencil tip, and (d) telescoping cane with a marshmallow tip.

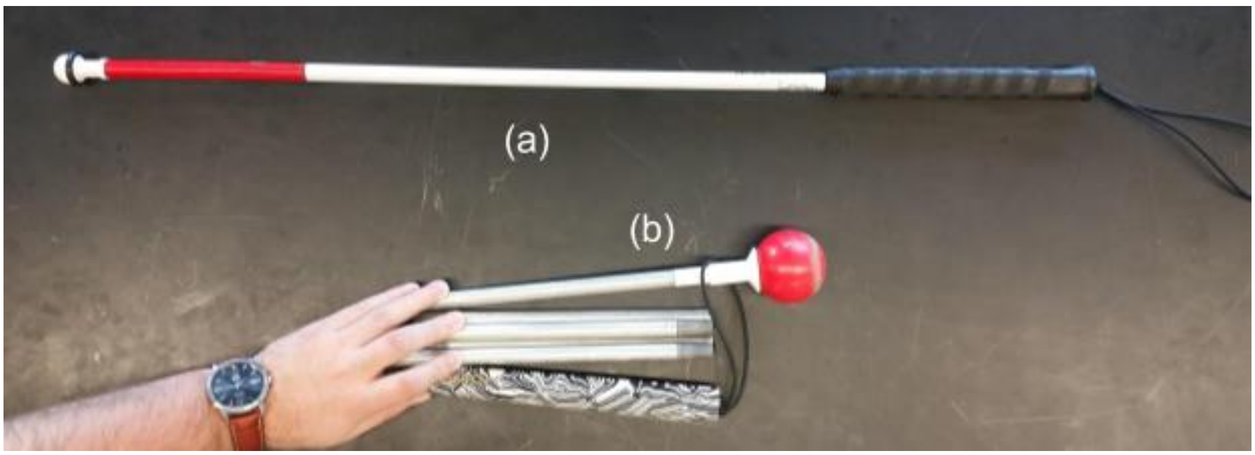

Figure 1.2: (a) Retracted fiberglass telescoping cane and (b) folded aluminum cane.

There are two common navigation techniques used with the white cane. In the two-point touch technique, the cane is swung rhythmically back and forth in front of the user and tapped on the ground in an ark slightly wider than the user's body. In the constant-contact technique, the cane tip maintains contact with the walking surface as it is swung back and forth. In both cases, the goal is for the cane to scan the ground location the user will step into.

1.2. Motivation for Project

The white cane is the most common mobility tool for people with visual impairment. Blind people have used a rod or staff to help move independently since antiquity, but the modern white cane was developed in the 1940s by Richard Hoover [1], [2]. Although research has continued on ways to improve its design, the white cane has not substantially changed in form since its introduction [1].

A cane user swings the cane in front of his body in order to preview the environment in front of him before walking into it [2]. This preview may be divided into three categories [3]: object preview, foot placement preview, and surface preview. Object preview is the detection of obstacles in the cane user's path of travel. These may include fire hydrants, sign or light posts, mailboxes or walls; object preview is achieved whenever the cane is swept in front of the user. Foot placement preview checks to make sure that the walking surface is clear and safe [3]. Surface preview detects changes in the walking surface such as cracks, curbs or stairs, or changes in elevation. Surface preview also considers changes in the texture of the surface (roughness), and happens any time the cane tip interacts with the ground. This project will deal with the role of vibration cues in the surface preview component of navigation.

It is important that a vision-impaired pedestrian is able to discriminate between different walking surfaces. For example, imagine the case where a white cane user is walking down a sidewalk and comes to an intersection. If there is no drop off from the curb into the street (as with a handicap-accessible ramp), the pedestrian may not have any other cue that he is walking into the road except for the change in surface from the concrete sidewalk to the asphalt road. If he does not notice the change in surface, he may be in danger from oncoming vehicles. Cane users may also pay attention to changes in the walking surface in order to navigate open spaces. For example, they may follow a sidewalk by noticing its edge against grass or against an adjacent parking lot. Texture discrimination is also important indoors, where some surfaces such as tile or linoleum may be slippery (as when wet), so extra care should be taken.

When the cane tip is scraped on the ground it creates vibration that travels up the length of the cane to the handle. This vibration is felt in the hand by the cane user, who uses it to interpret the texture of the walking surface [4]. In other words, the vibration felt in the hand is what gives cues to the cane user about the walking surface on which he is travelling. The goal of this project is to investigate how cane users interpret these vibratory cues to learn about the walking surface. The cane tip also creates sound which may help identify the walking surface, and echoes from this sound can also help identify obstacles [5].

Instrumentation can be used to measure the vibration of a cane while it is in use for navigation, in order to measure how the cane vibrates under different conditions. In this way, a user can be asked to perform a navigation task, and we can simultaneously measure the vibration response of the cane as well the performance of the user in that task. This allows the identification of specific parameters that a cane user might be paying attention to during the surface preview task, such as the frequency content of the cane vibration, or its amplitude.

With information about the nature of these vibratory cues, canes can be designed that accentuate the ability of the user to differentiate between surfaces. By modifying the material or geometry of a cane, it may be possible to tailor its vibration to the user. This will allow the user to be more sensitive to changes in the walking surface, improving his or her safety and mobility.

1.3. Overview of Project

Chapter 2 provides a literature survey on factors influencing white cane performance, instrumenting white canes and human perception of texture and roughness. Chapter 3 describes the methodology of the texture discrimination experiment and Chapter 4 provides analysis on the results. Chapter 5 shows a pilot study that uses an instrumented cane to investigate the role of vibration cues in the detection of drop-offs in the walking surface. Chapter 6 provides concluding remarks and recommendations for future work.

CHAPTER 2

LITERATURE SURVEY

2.1. Factors Influencing White Cane Performance

There is a small body of research that deals with the physical characteristics that affect a user's ability to navigate. In [6], Rodgers found that heavier canes cause fatigue more quickly than lighter ones, reducing the accuracy with which participants placed the cane tip as the navigation task went on. However, the distribution of weight did not significantly impact performance. Weight was not significant in the ability to discriminate surface textures, but performance increased as the stiffness of the cane shaft was increased. He notes that the canes used in the study showed increasing resonant frequencies as stiffness was increased, although the evidence was not sufficient to suggest that this was the cause of better performance. He suggests further study on the way in which cane users acquire information from vibrations felt in the hand.

The length of a user's cane may be important for navigation performance. Rodgers and Wall Emerson found that when canes were either much longer or much shorter than the length suggested by the sternum method, they were less effective at detecting drop-offs in the walking path using the two-point touch technique [1]. Kim and Wall Emerson found that cane length was not significant to drop-off detection, although they investigated the constant contact scanning technique. They also found that drop-off detection performance improves as the drop-off height increases [7].

Cane technique also impacts performance. The constant contact technique is more effective than two-point touch at detecting drop-offs, when considering both detection rate and detection threshold [2], [8]. This difference is more pronounced for inexperienced cane users than for experienced ones [9]. Younger cane users, and those who lost vision earlier in life, perform better than those who are older or lost vision at an older age [10]. A heavier cane performs better at detecting drop-offs when using the constant contact technique, while a flexible cane performs better when using the two-point touch technique [11]. Constant contact is more effective than two-point touch at detecting obstacles in the walking path that are very short (on the order of one inch tall); for taller obstacles, both techniques perform equally well [12].

The kind of cane tip used may also affect navigation performance. In particular, tips with a small diameter, such as a pencil tip, are more likely to get caught in surface irregularities like sidewalk cracks, tree roots, holes or metal grates, when compared to a larger tip such as a marshmallow or ball tip. The larger tips are more likely to glide over small obstructions [6].

2.2. Instrumenting Canes

This project deviates from most of the literature that involves adding instrumentation to white canes, in that this work adds sensors to canes in order to quantify the way that blind people use canes as a navigation tool. Most examples of instrumented white canes fall into the category of Electronic Travel Aids (ETAs). These are devices that use sensors to help a blind person avoid obstacles or navigate to his destination more efficiently.

A number of US patents describe canes that aim to improve detection of obstacles that are either beyond the reach of the cane tip, or are at levels above the ground. The Mobility cane for the blind (US 4280204 A, 1981) suggests the use of an electrostatic transducer to detect obstacles at head or chest level. The user is alerted by audible signal in an ear piece. The Electronic blind guidance cane (US 20060028544 A1) performs the same function using an optical sensor; while the Management and navigation system for the blind (US 20060129308 A1) proposes adding a Radio Frequency Identification (RFID) tag reader to a cane, allowing the user to follow a “trail” of preplaced markers that lead to his or her desired destination.

Hesch and Roumeliotis developed a method to determine a blind pedestrian’s position in a known building using a gyroscope, pedometer and laser range finder mounted on the cane handle. After developing a model of an indoor space, this method could be used to provide auditory directions to the blind person [13]. Gallo et al. attached optical and ultrasonic sensors to a cane, then communicated the presence of walls and obstacles to the user through haptic feedback [14]. Other ETAs that are not mounted to a cane may attach sensors to glasses [15]–[17], shoes [16], or a vest worn by the user [18], and typically use auditory cues to guide the user to his destination or to help him avoid obstacles.

In one noteworthy study, a cane was instrumented with 3-axis gyroscope, a 3-axis accelerometer, and a small camera observing the cane grip, in order to measure the grip and sweep characteristics of cane users during the constant contact technique. It found that the grip used varied widely between participants, but that participants used the same grip consistently while in motion. Cane tilt angle (the angle the cane makes with the ground) and cane roll angle (rotation in the hand in the axial direction) show little variation between participants. Cane sweeping angle (how wide an arc is swept) and sweeping frequency vary considerably between participants, but show little variation between trials of the same participant. This information can help inform the design of future ETAs [19].

2.3. Perception of Vibration and Roughness

To understand how a white cane user previews the walking surface through vibration, it is important to be familiar with the way in which people perceive vibration and roughness through the hand. The sensitivity of the human hand to vibration varies with frequency and with position on the hand [20], [21]. That is, the palm and fingertips may show different sensitivities to the same frequency. In general, the hand is the most sensitive to vibration between 100 and 200 Hz, and becomes less sensitive above or below this range [20]–[22].

Vibration perception is controlled by four types of mechanoreceptors in the hand. Slowly adapting type I and type II (SA-I and SA-II) receptors are sensitive to skin indentations and stretching respectively, and respond to low frequency vibration (up to about 4 Hz). Rapidly adapting type I (RA-I) receptors perceive the velocity of deformation in the skin, and are sensitive to vibration up to about 80 Hz. Rapidly adapting type II (RA-II) receptors perceive the acceleration of skin deformation in the frequency range 40 – 500 Hz, with highest sensitivity between 100 and 200 Hz [20], [23]. The RA-II receptors are the most important for perceiving the roughness of a surface [23].

When using a probe to explore a textured surface, as with a white cane, the perceived roughness of the surface depends both on the geometric features of the probe tip and surface, and on the exploration parameters like scraping speed [24]. For relatively uniform surfaces, increasing the exploration speed causes the surface to be perceived as smoother; however, for surfaces that are more sparsely populated with features (grooves, bumps or holes), increasing the exploration speed increases perceived roughness [25]. This transition happens at the "drop point," the geometric condition when the spacing between features is about the same as the probe tip diameter. At this point, the probe tip goes from riding on top of the features to falling between them and riding on the substrate [24]. Sensitivity to changes in surface roughness decreases as speed is increased [24]. Perceived roughness also increases as the applied force on the probe increases [26]. It has been suggested that this increase is due to an increase in the amplitude of vibration in the probe [24].

CHAPTER 3

METHODOLOGY: TEXTURE DISCRIMINATION EXPERIMENT

This chapter introduces the texture discrimination experiment in Section 3.1 and describes the setup in Section 3.2. Section 3.3 outlines the experimental procedure, and Section 3.4 describes the information that was recorded.

3.1. Introduction

Texture discrimination is an important part of the surface preview navigation task, as a blind pedestrian must be able to identify a change in the walking surface. This is important, for example, at the interface between a concrete sidewalk and asphalt road or parking lot, so that the cane user will not step out into the path of an oncoming vehicle.

A forced-choice experiment was designed to measure the ability of cane users to discriminate surface texture. The experiment investigated two factors for their effect on correct identification rate: cane flexibility and swipe speed. Aluminum plates were machined with long parallel grooves that varied in width and depth, in order to create a set of surfaces with varying roughness. Two plates were set side by side in each trial, the participant scraped the cane tip once across the pair of them, and then determined which one was rougher (that is, which plate has the larger grooves). Accelerometers were mounted to the cane so that its vibration could be measured as the test was being conducted. The participant's choice was noted for each trial, along with whether it was correct or incorrect, and then the vibration of the cane was reviewed to look for cues that the participant may have used to make the decision.

3.2. Experiment Setup

The participants were 11 graduate students in the Orientation and Mobility (O&M) program at Western Michigan University, who participated as part of a research methods course (BLS 6100 Assisted Research). Ten of the participants were sighted while one had some vision impairment (20/500 visual acuity with no field loss, caused by degenerative myopia and congenital nystagmus). All participants had training in using a white cane as part of the O&M curriculum.

The two canes used in the experiment were identical except for shaft material. The stiffer cane was made from pultruded carbon, while the more flexible cane was made from poplar wood. A foam handle (17g) and plastic ball tip (51g) was attached to each cane. Figure 3.1 shows the two canes, while Table 3.1 gives properties and dimensions, including total cane mass. Rigidity was measured in a previous study by cantilevering the cane shaft, adding mass to the free end, then measuring the deflection of the free end (see [11]).

Figure 3.1: Poplar (top) and pultruded carbon (bottom) canes.

Table 3.1: Properties and dimensions of both canes.

Cane	Pultruded Carbon	Poplar
Length (m)	1.372	1.372
Outer Diameter (mm)	12.5	12.7
Inner Diameter (mm)	10.4	Solid
Total Mass (g)	153	159
Rigidity (N/m)	149.5	34.5

Two accelerometers were mounted on each cane to measure its vibration. Figure 3.2 shows the location of each accelerometer. One was placed just above the cane tip in order to more closely measure the excitation of the cane through the tip, while the other was placed just below the start of the foam grip to more closely measure the vibration felt in the hand. Using two accelerometers at opposite ends of the cane also allowed a Frequency Response Function (FRF) to be calculated, which is a measure of how vibration changes as it travels up the cane shaft. Both accelerometers were placed so that they were on top of the cane when held by a right-handed user, so that tapping on the ground was measured as a positive acceleration. Accelerometers were attached to the canes with super glue. Accelerometers were not attached to the foam cane handle or to the participant's hand. Both are soft when compared to the cane shaft material, and so vibration would not be transferred as well to the sensor.

The accelerometers were PCB Piezotronics model 352C22 single axis sensors, selected because they are lightweight (0.5 g each), in order to prevent mass loading of the cane. Mass loading is the condition where, by attaching large accelerometers to a small structure, the added mass of the sensors actually changes the natural vibration of the structure. During the experiment, the accelerometers were connected to a National Instruments NI-9234 analog data acquisition module and NI-USB-9162 chassis. M&P International Smart Office Analyzer software was used to take measurements on a Windows laptop. Figure 3.3 shows a block diagram of the data acquisition setup.

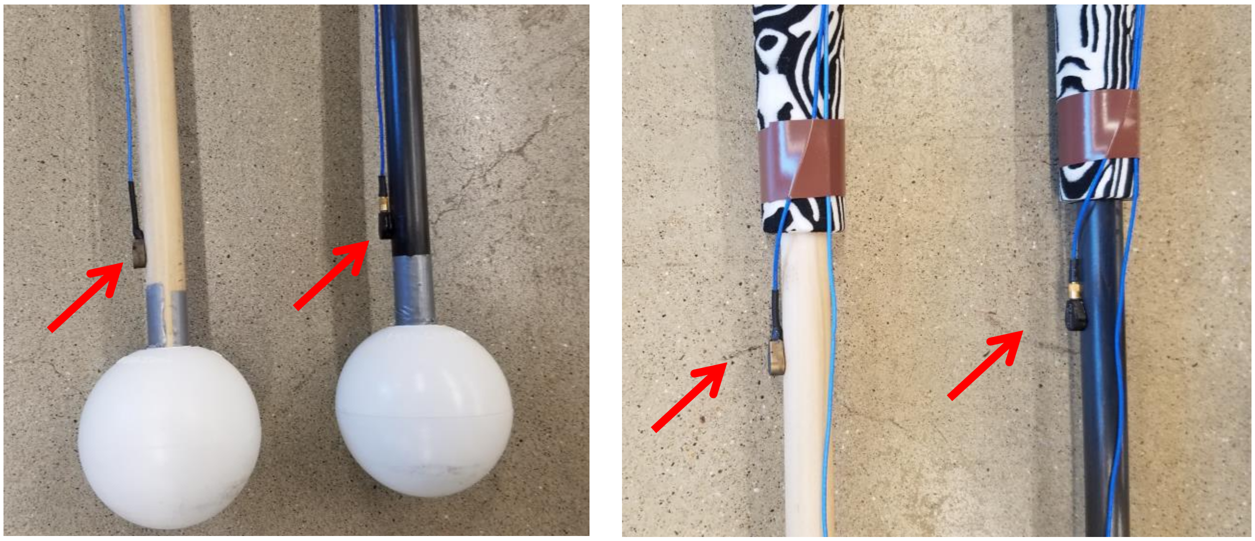

Figure 3.2: Accelerometer placement. Arrows indicate accelerometers.

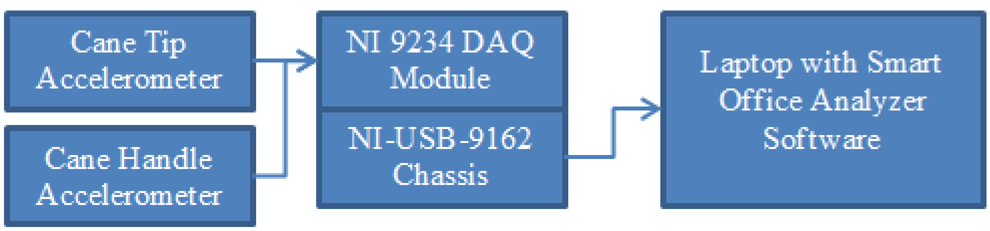

Figure 3.3: Block diagram of data acquisition setup for texture discrimination experiment.

The textured plates were milled from 24x12x0.5 inch aluminum blanks. Grooves were cut on the face of each plate parallel to the 12 inch side, so they covered 22 inches of the plate face. This left a 2x12 inch smooth section on one end of the plate face. Another set of grooves with a different dimension was cut on the reverse face of the plate, to reduce material costs.

The groove width matched the space between adjacent grooves, while the groove depth was one third of that dimension. Groove width varied from 1.5 mm to 5.5 mm in 0.5 mm increments, for a total of nine textures. The groove widths were desired to be small compared to the size of the cane tip, so that the tip would glide over the plate and not get stuck in the grooves, but it was impractical to machine grooves smaller than 1.5 mm because of the small cutting tool size and number of grooves required on a surface. Figure 3.4 shows the dimensions of the groove and spacing between them. Table 3.2 gives a list of relevant plate dimensions. Figure 3.5 shows the 2 mm and 4.5 mm plates side by side. Note the flat area at one end of each plate.

A wooden frame was built to align two plates together end to end, so that the participant could scrape across a single 12x48 inch surface that had a different roughness on each half. Figure 3.6 shows the frame with two plates. The frame had raised edges on each 12-inch side and the 48-inch side further from the participant, in order to keep the cane tip from sliding off of the surface. It also held the plates just off the floor and left one side easily accessible, so that it is easy to remove a plate and put another one in that had different roughness.

Table 3.2: Grooved plate dimensions.

Plate	**Groove Width [mm]**	**Groove Depth [mm]**	**Number of Grooves**
1	1.5	0.495	183
2	2.0	0.660	138
3	2.5	0.825	109
4	3.0	1.000	93
5	3.5	1.155	79
6	4.0	1.330	72
7	4.5	1.485	63
8	5.0	1.667	56
9	5.5	1.815	50

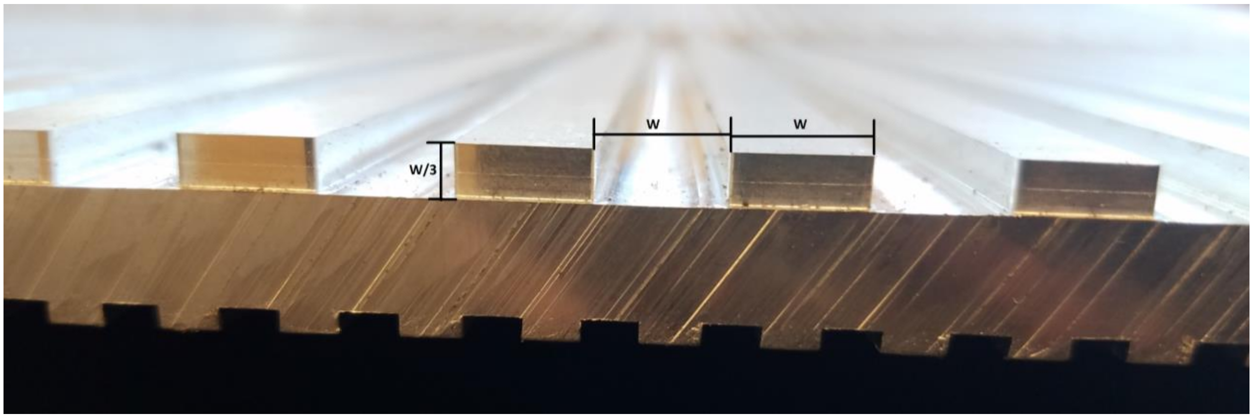

Figure 3.4: Groove dimensions.


Figure 3.5: Two millimeter (left) and 4.5 millimeter (right) grooved aluminum plates.

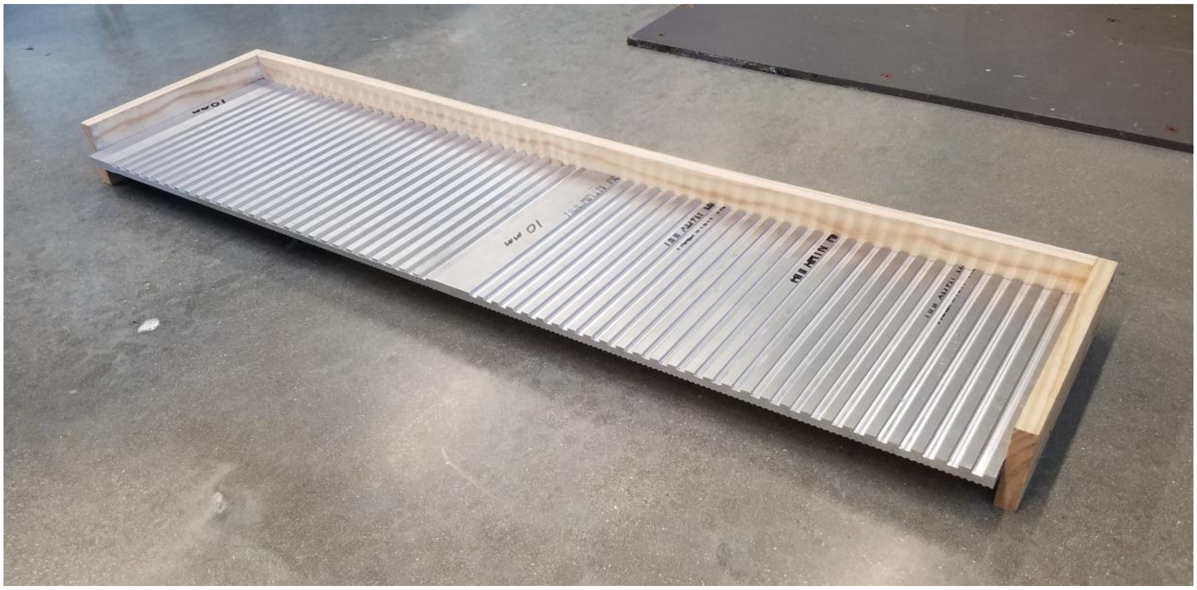

Figure 3.6: Wooden frame with two textured plates.

3.3. Experimental Procedure

The experiment was performed in the WMU Noise and Vibration Laboratory in Floyd Hall. At the beginning of a session, the participant was introduced to the experiment and asked to sign an informed consent form. Participants wore a blindfold and headphones (Radio Shack Full-Size Headphone 33-1225) during all trials, in order to prevent them from relying on visual or auditory cues. Pink noise was played through the headphones with an MP3 player (iPod Touch) to mask the sound of the plates being scraped. A metronome was superimposed on the pink noise to guide the participant’s swipe speed.

Figure 3.7 shows a trial with a participant. For each trial, the participant was placed in front of two plates in the wooden frame. He or she picked up the cane tip and set it on the left plate, all the way to the left so that it rested up against the wooden frame. He or she then scraped to the right in one motion until the cane contacted the wooden frame on the right side, and then indicated verbally which plate was rougher by saying “left” or “right.” The cane tip was picked up so that the pair of plates could be changed, then the participant was tapped on the shoulder to indicate that they could scrape the next pair of plates.

Figure 3.7: Participant in texture discrimination experiment.

In the low speed condition, the metronome was set to 120 beats per minute with every fourth beat accented. The participant was instructed to start a scrape at an accented beat, and move at a speed such that they ended the scrape at the next accented beat, so that the scrape took approximately two seconds. In the high speed condition, the metronome was set to 320 beats per minute with every fourth beat accentuated, so that the scrape took approximately 0.75 seconds. These two speeds were selected to be substantially different, while still within a reasonable range that a blind pedestrian might use during navigation. The participant was allowed to practice several times before the first trial, to get used to swiping at the required speed. Measuring the scrape time in vibration measurements shows that this method was effective at producing two distinctly different scrape speeds ($p < 0.001$, low speed mean = 1.780 seconds, SD = 0.163, high speed mean = 0.750 seconds, SD = 0.163).

The 3.5 mm plate was used as a reference plate, so it was used in every trial. In each sample, it was placed side by side with another plate that was smoother (1.5, 2.0, 2.5 or 3.0 mm) or rougher (4.0, 4.5, 5.0 or 5.5 mm); no trials considered two plates with equal roughness. The smooth section on each plate face was placed in the center, so that the participant scraped over one texture, then approximately four inches of smooth aluminum, then the other texture. This was done to provide a clear distinction between one side and the other for the participant, and to create an indication in the vibration data that could be used to distinguish the two plates from each other.

Each participant was evaluated in a total of 128 trials, in four blocks of 32 trials each. Each block was in one of the following conditions: rigid cane with low swing speed, rigid cane with high swing speed, flexible cane with low swing speed, or flexible cane with high swing speed. Within each block, the 3.5 mm plate was compared to every other roughness four times. To control for plate order, the reference plate was placed on the left and right sides for two trials each, and the whole block of 32 trials was randomized.

3.4. Data Collected

The choice of the participant was scored as correct or incorrect after each trial. However, the participant was not given feedback about whether the plate was correct or incorrect. The scores were used to find average detection rates under each condition. Results from one participant are shown in Table 3.3 (for both rigid cane conditions) and Table 3.4 (for both flexible cane conditions). Complete results are included in Appendix B.

The output of the two accelerometers was recorded using Smart Office Analyzer software (M&P International). The software was set to record the time record both accelerometer signals after being manually triggered by the operator. Although the low speed condition targeted a two second cane swing, Smart Office was set to record for 4.8 seconds, to make sure that the whole scrape would be recorded. Recordings were truncated by the experimenter after the scrape was finished.

The sample rate was set to 10,240 Hz. This value was selected after a pilot study found that spectral energy in the cane was mostly in the range of frequencies below 4 kHz. Furthermore, because the human hand becomes less sensitive to vibration above 500 Hz, as discussed earlier, it seems unlikely that frequencies higher than 500 Hz are important for texture discrimination.

Figure 3.8 shows the time record of the tip accelerometer during three separate trials. All three are for the same subject, in the rigid cane low speed condition; they correspond to samples five, six and nine in Table 3.3. The total recording time for each sample varies between four and five seconds long, and the actual portion of interest (the scrape) is in a different section of each sample.

Table 3.3: Sample results for rigid cane conditions.

Sample Number	Condition	Left Plate [mm]	Right Plate [mm]	Correct 1 = Y 0 = N	Sample Number	Condition	Left Plate [mm]	Right Plate [mm]	Correct 1 = Y 0 = N
1	Rigid Low Speed	5.5	3.5	1	33	Rigid High Speed	2.5	3.5	1
2	Rigid Low Speed	3.5	2.5	1	34	Rigid High Speed	3.5	5.5	1
3	Rigid Low Speed	3.5	4.0	1	35	Rigid High Speed	3.5	3.0	1
4	Rigid Low Speed	3.5	4.5	1	36	Rigid High Speed	4.0	3.5	0
5	Rigid Low Speed	4.0	3.5	1	37	Rigid High Speed	3.5	2.5	1
6	Rigid Low Speed	3.5	2.0	1	38	Rigid High Speed	3.5	5.5	1
7	Rigid Low Speed	4.5	3.5	0	39	Rigid High Speed	5.0	3.5	1
8	Rigid Low Speed	3.5	3.0	0	40	Rigid High Speed	2.5	3.5	0
9	Rigid Low Speed	2.0	3.5	1	41	Rigid High Speed	3.5	2.0	1
10	Rigid Low Speed	1.5	3.5	1	42	Rigid High Speed	3.5	4.5	1
11	Rigid Low Speed	5.5	3.5	1	43	Rigid High Speed	2.0	3.5	1
12	Rigid Low Speed	3.5	4.5	1	44	Rigid High Speed	4.5	3.5	0
13	Rigid Low Speed	2.5	3.5	1	45	Rigid High Speed	3.5	1.5	1
14	Rigid Low Speed	3.5	2.0	1	46	Rigid High Speed	3.5	4.0	1
15	Rigid Low Speed	3.0	3.5	1	47	Rigid High Speed	1.5	3.5	1
16	Rigid Low Speed	5.0	3.5	1	48	Rigid High Speed	1.5	3.5	1
17	Rigid Low Speed	2.5	3.5	1	49	Rigid High Speed	4.0	3.5	1
18	Rigid Low Speed	2.0	3.5	1	50	Rigid High Speed	3.0	3.5	1
19	Rigid Low Speed	3.0	3.5	0	51	Rigid High Speed	3.5	5.0	1
20	Rigid Low Speed	1.5	3.5	1	52	Rigid High Speed	5.0	3.5	1
21	Rigid Low Speed	3.5	5.0	1	53	Rigid High Speed	3.5	4.5	0
22	Rigid Low Speed	3.5	2.5	1	54	Rigid High Speed	3.5	2.0	1
23	Rigid Low Speed	3.5	3.0	1	55	Rigid High Speed	4.5	3.5	0
24	Rigid Low Speed	4.0	3.5	0	56	Rigid High Speed	3.5	2.5	1
25	Rigid Low Speed	5.0	3.5	1	57	Rigid High Speed	5.5	3.5	1
26	Rigid Low Speed	4.5	3.5	0	58	Rigid High Speed	2.0	3.5	1
27	Rigid Low Speed	3.5	5.5	1	59	Rigid High Speed	3.0	3.5	0
28	Rigid Low Speed	3.5	1.5	1	60	Rigid High Speed	3.5	4.0	1
29	Rigid Low Speed	3.5	5.0	1	61	Rigid High Speed	3.5	1.5	1
30	Rigid Low Speed	3.5	5.5	1	62	Rigid High Speed	3.5	5.0	1
31	Rigid Low Speed	3.5	4.0	1	63	Rigid High Speed	3.5	3.0	1
32	Rigid Low Speed	3.5	1.5	1	64	Rigid High Speed	5.5	3.5	1

Table 3.4: Sample results for flexible cane conditions.

Sample Number	Condition	Left Plate [mm]	Right Plate [mm]	Correct 1 = Y 0 = N	Sample Number	Condition	Left Plate [mm]	Right Plate [mm]	Correct 1 = Y 0 = N
65	Flexible Low Speed	3.5	2	1	97	Flexible High Speed	3.5	5.5	1
66	Flexible Low Speed	4.5	3.5	1	98	Flexible High Speed	3	3.5	1
67	Flexible Low Speed	2	3.5	1	99	Flexible High Speed	2	3.5	1
68	Flexible Low Speed	3.5	4.5	1	100	Flexible High Speed	3	3.5	1
69	Flexible Low Speed	2	3.5	1	101	Flexible High Speed	3.5	2	1
70	Flexible Low Speed	3.5	5.5	1	102	Flexible High Speed	4.5	3.5	1
71	Flexible Low Speed	3.5	4	1	103	Flexible High Speed	3.5	4	1
72	Flexible Low Speed	5	3.5	1	104	Flexible High Speed	3.5	5	1
73	Flexible Low Speed	3.5	3	0	105	Flexible High Speed	4	3.5	0
74	Flexible Low Speed	3.5	5.5	1	106	Flexible High Speed	5	3.5	1
75	Flexible Low Speed	3.5	2.5	1	107	Flexible High Speed	3.5	1.5	1
76	Flexible Low Speed	3.5	5	1	108	Flexible High Speed	3.5	4	1
77	Flexible Low Speed	5	3.5	1	109	Flexible High Speed	3.5	5	1
78	Flexible Low Speed	3.5	5	1	110	Flexible High Speed	3.5	2.5	1
79	Flexible Low Speed	3.5	2.5	1	111	Flexible High Speed	3.5	5.5	1
80	Flexible Low Speed	1.5	3.5	1	112	Flexible High Speed	5	3.5	1
81	Flexible Low Speed	5.5	3.5	1	113	Flexible High Speed	5.5	3.5	1
82	Flexible Low Speed	3.5	1.5	1	114	Flexible High Speed	3.5	2	1
83	Flexible Low Speed	5.5	3.5	1	115	Flexible High Speed	2	3.5	1
84	Flexible Low Speed	3	3.5	0	116	Flexible High Speed	2.5	3.5	1
85	Flexible Low Speed	4	3.5	1	117	Flexible High Speed	4	3.5	0
86	Flexible Low Speed	2.5	3.5	0	118	Flexible High Speed	3.5	1.5	1
87	Flexible Low Speed	3.5	1.5	1	119	Flexible High Speed	5.5	3.5	0
88	Flexible Low Speed	4.5	3.5	1	120	Flexible High Speed	3.5	4.5	1
89	Flexible Low Speed	3.5	2	1	121	Flexible High Speed	1.5	3.5	1
90	Flexible Low Speed	1.5	3.5	1	122	Flexible High Speed	3.5	3	1
91	Flexible Low Speed	3.5	4	1	123	Flexible High Speed	1.5	3.5	1
92	Flexible Low Speed	3	3.5	0	124	Flexible High Speed	3.5	3	1
93	Flexible Low Speed	3.5	4.5	1	125	Flexible High Speed	2.5	3.5	1
94	Flexible Low Speed	2.5	3.5	0	126	Flexible High Speed	3.5	4.5	0
95	Flexible Low Speed	3.5	3	1	127	Flexible High Speed	4.5	3.5	0
96	Flexible Low Speed	4	3.5	1	128	Flexible High Speed	3.5	2.5	1

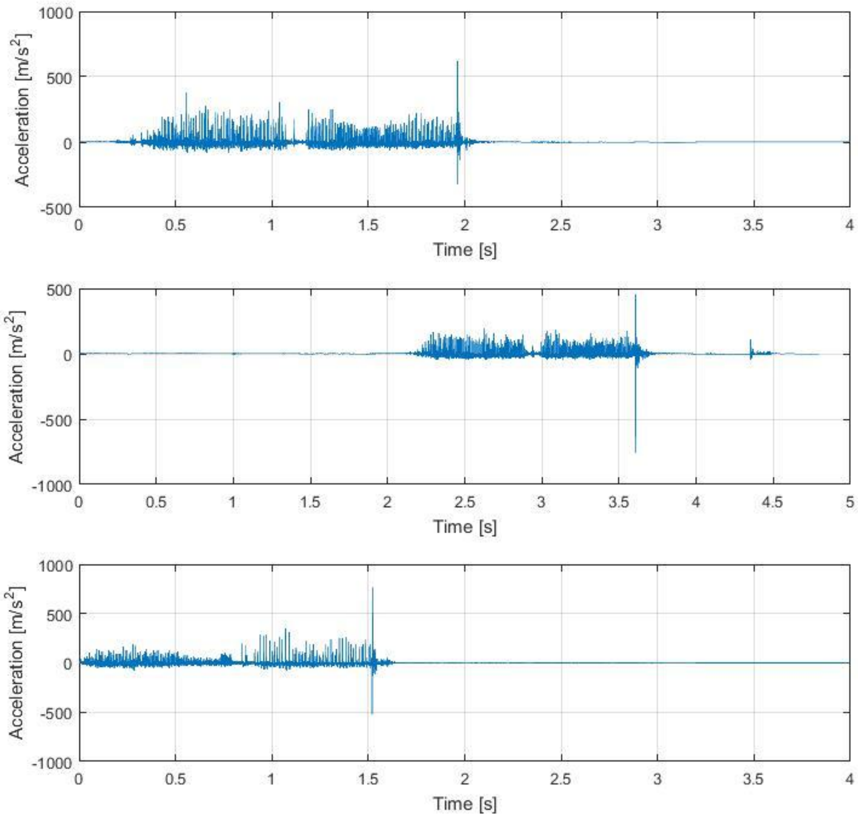

Figure 3.8: Accelerometer time data from three trials.

The actual scraping portion of the time signal is the higher amplitude section of the plot; the participant consistently took about 1.5 seconds for each of the scrapes. The high-amplitude peak at the end of the time signal is caused by the cane impacting the wooden frame at the right side of the second plate.

Figure 3.9 shows the same three samples, but trimmed to remove the extra data before and after the plate scrape. Note that the high-amplitude peak at the end of the time signal was trimmed. Inspecting these three samples, it is possible to identify the point where the cane tip crossed over from the first plate to the second one. This is characterized by a short period of low amplitude vibration as the cane tip slides over the smooth section on the first plate, followed by a peak as the cane tip crosses the interface of the two aluminum plates, then another short period of low amplitude vibration as the cane tip slides across the smooth section on the second plate. Figure 3.10 indicates the crossover point in each sample with an arrow.

By identifying the crossover point between the left and right plates, it is possible to compare the nature of the cane vibration from one half to the other, and look for differences that the user may be interpreting to make a decision about the relative roughness of the two plates.

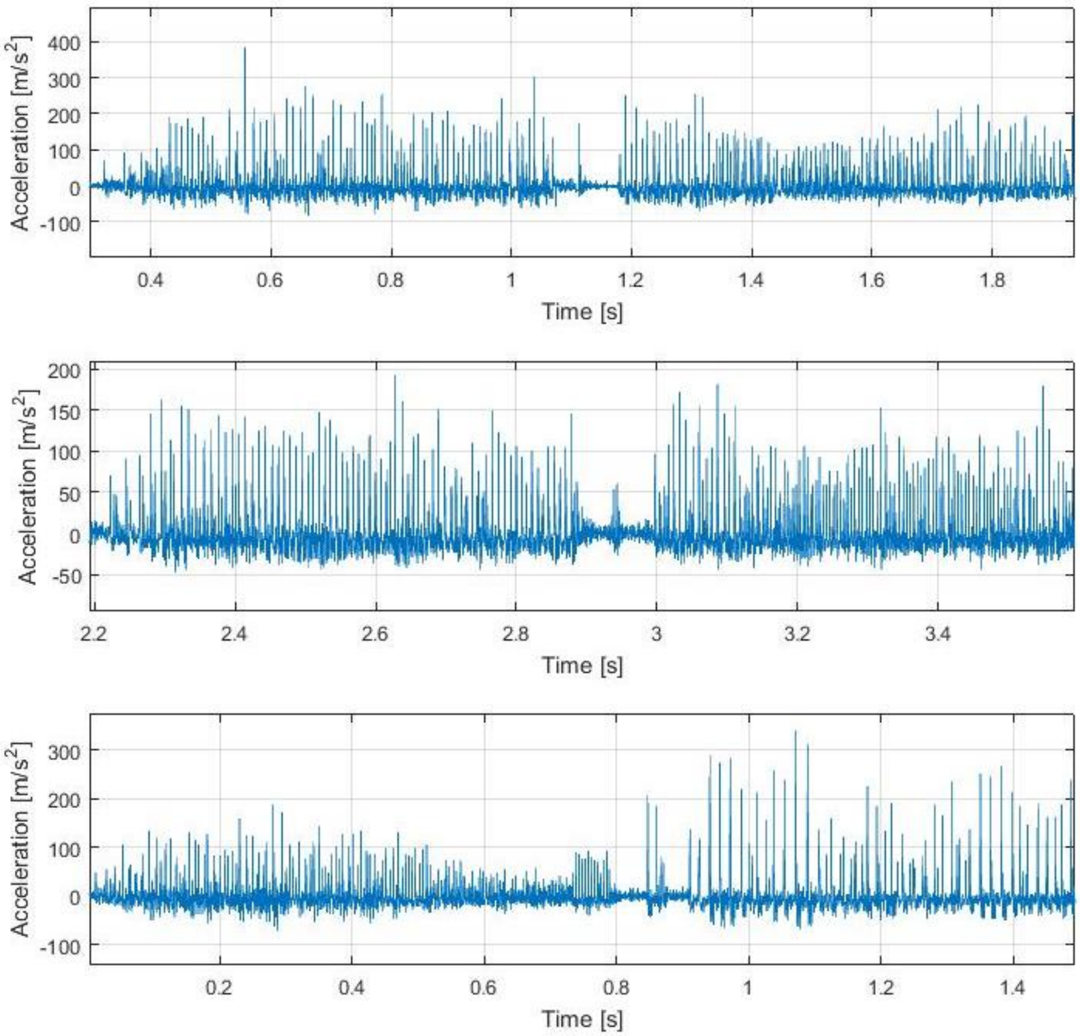

Figure 3.9: Trimmed accelerometer time data.

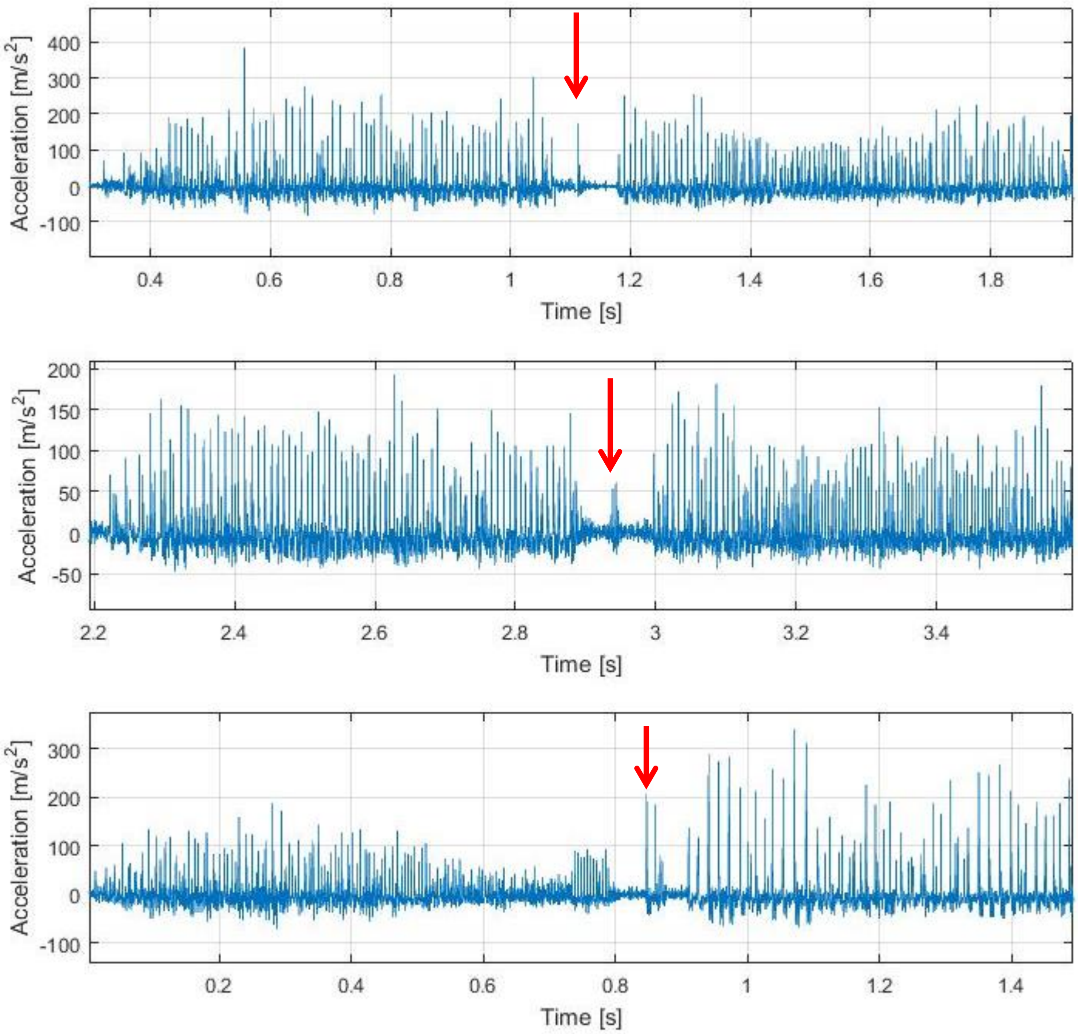

Figure 3.10: Location of transition between left and right textured surface.

CHAPTER 4

ANALYSIS

This chapter describes the methods used to interpret and process the results from the experiment. First, a statistical test was performed to find out how cane rigidity and swipe speed impact the overall participant correct identification rate in Section 4.1. Then the cane vibration measurements were post processed in Section 4.2, and two methods are developed to select the rougher of the two plates by analyzing the vibration of the cane. The first method, outlined in Sections 4.3 - 4.6, identifies high-amplitude peaks in the vibration that seem to be caused by individual grooves in the textured plates, and makes a decision about the relative plate roughness based on how frequently these peaks occur for each plate. The second method, in Sections 4.6 and 4.7, selects the rougher plate based on the overall amplitude of the vibration signal. Discrepancies are addressed in Section 4.8, then other less effective methods are briefly discussed in Section 4.9, and then the peak frequency and peak amplitude methods are applied to the data from a small pilot study in Section 4.10. The chapter is summarized in Section 4.11.

4.1. Participant Performance

An ANOVA statistical analysis was performed on the participant detection results using Minitab software. Participants performed significantly better in the low speed condition than the high speed condition (F = 11.76, degrees of freedom = 1, p value = 0.001, low speed mean = 84.0% correct, high speed mean = 76.7% correct), but there was no significant difference between the rigid and flexible canes (p = 0.382). The interaction between speed and rigidity was not significant (p = 0.545).

The expectation was that participants would correctly judge the rougher texture more often in the low speed condition. As noted earlier, it has been shown that when feeling texture through a probe, sensitivity to changes decreases with increasing speed [24], [25]. However, it was expected that the rigid cane would also perform better than the flexible one in agreement with Rodger's findings [6]. It is possible that there is some effect of rigidity on detection rate, but that this experiment did not perform enough replications to capture it, or that the difference in rigidity between the two canes was not large enough. Note that in this study, each participant was presented with a pair of plates only four times in each block condition. Repeating the study with more replications or a larger difference in cane rigidity may help to capture the effect of rigidity on texture discrimination performance.

4.2. Post Processing of Vibration Data

Figure 4.1 shows the output of the tip accelerometer during one trial in the rigid low speed condition (sample 27 in Table 3.3); the left plate is the 3.5 mm reference, and the right is the 5.5 mm plate. The time when the cane went over the interface of the two plates (around 0.75 seconds) can be identified visually by the low amplitude section, single peak, and second low amplitude section. Figure 4.2 shows the two plates from the perspective of the participant.

In this example, vibration associated with each plate looks somewhat different. Compared to the left (3.5 mm) plate, the right one looks as if it has peaks with higher average amplitude that are spaced further apart in time. Qualitatively, the vibration associated with the right plate "looks rougher." This example is typical of many of the samples in this experiment. By dividing the accelerometer output into two halves at the plate interface, the vibration of each half can be quantified separately and the rougher plate selected by comparing the two vibration profiles.

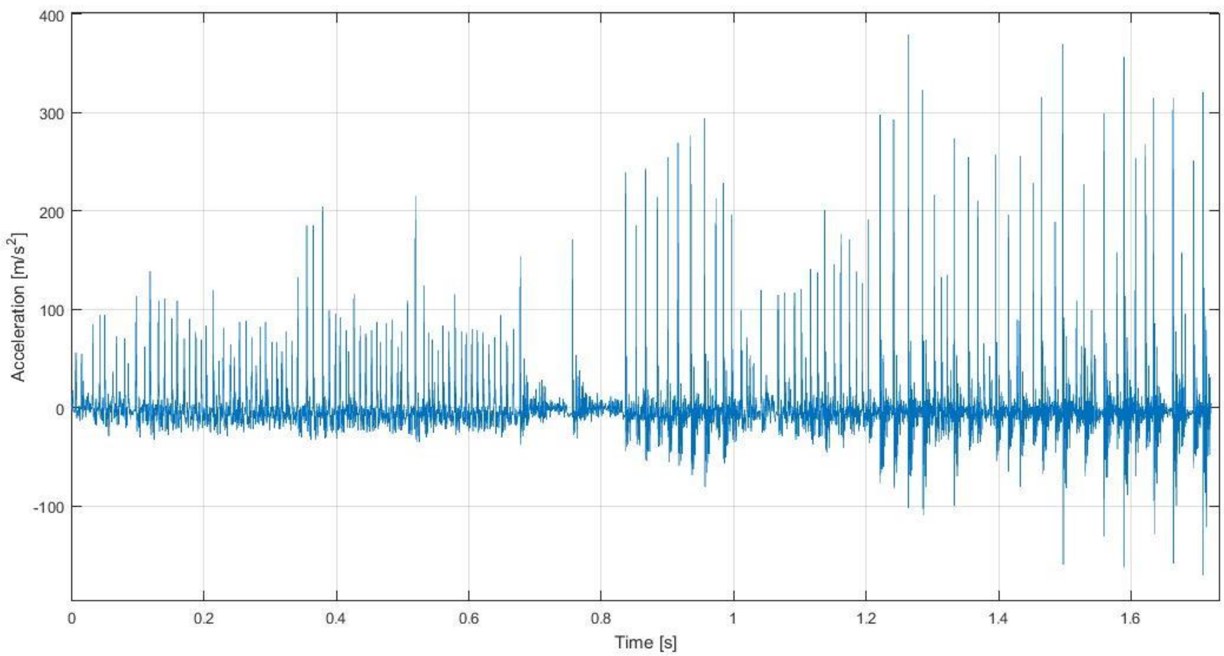

Figure 4.1: Tip accelerometer response for Sample 27 in rigid low speed condition.

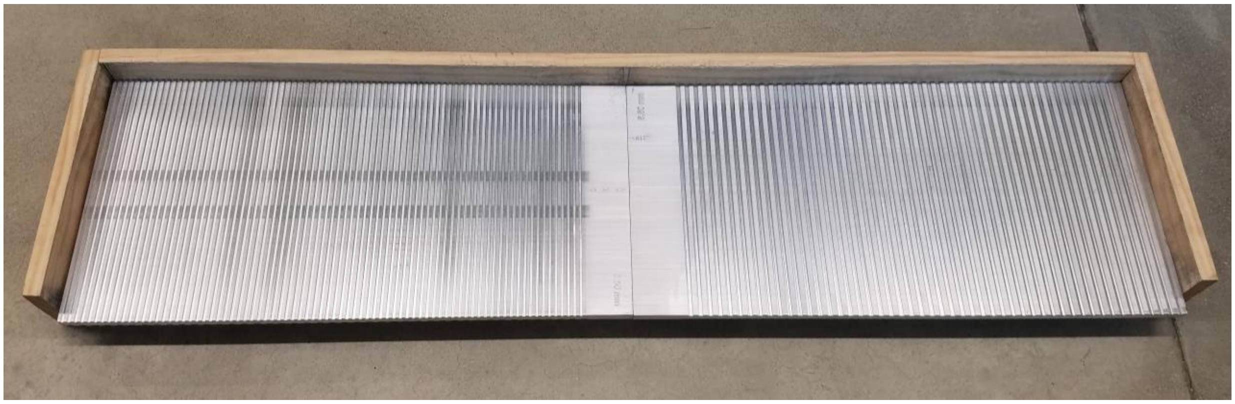
Figure 4.2: The 3.5 mm and 5.5 mm plates, as used in Sample 27.

The acceleration measurement from each trial was exported from Smart Office Analyzer as a MATLAB structure for post processing. Although each cane user participated in 128 trials, not every trial was recorded successfully. In some cases, the software operator triggered the recording too late and truncated the left plate, or triggered it too early and truncated the right plate. The operator missed a few recordings entirely. Samples that seemed to have a significant part of one plate missing were not considered for analysis. Of the 1408 total samples, 1369 were recorded and post processed.

All of the accelerometer signal post processing throughout the rest of this work was performed on the response of the sensor placed near the cane tip, unless noted otherwise. The response of this accelerometer more closely captures the result of the interaction of the cane tip and surface, so changes in the vibration response due to the surface texture are more obvious. The acceleration measured at the handle has been transmitted through the cane shaft, and the cane resonance can obscure these differences.

A MATLAB script was written to plot each raw time file one at a time, and prompt the user to manually identify the beginning and end of the scrape. The file is plotted again, showing only the plate scrape, and prompts the user to click on the interface of the two plates. This process allows the beginning, crossover point and end of each sample to be quickly identified. The script outputs an array in which the first column holds the sample number, the next three columns give timestamps for the beginning, middle and end of the scrape, and the last three columns give the array index of each of the events in the raw data file. A second MATLAB script will use the raw data file and analyze only the section that contains the plate scrape.

The previous step also provided an opportunity to visually inspect every sample again and remove any bad samples. Two common issues with the vibration recording were identified at this point. First, some of the samples that were exported into MATLAB were still missing a significant part of one plate. Samples were eliminated if a majority of one side was missing. Figure 4.3 shows two examples of low speed samples that were truncated in the recording, while Figure 4.4 shows two examples of high speed samples that were truncated. If it seemed that one side in a sample was truncated, but the remaining portion was large enough to make a representative measurement of the vibration on that plate, the sample was not eliminated.

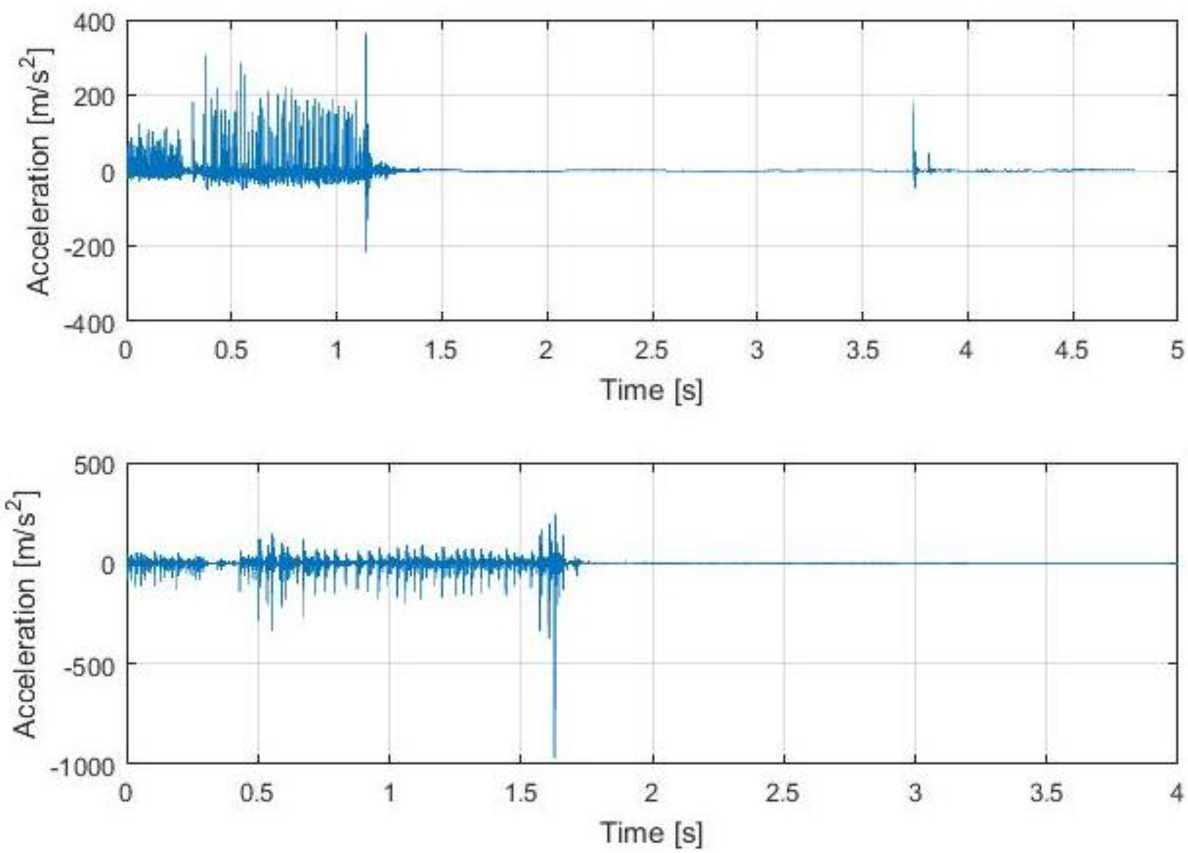

Figure 4.3: Two samples with truncated plate scrape, in low speed condition.

The second issue often noted at this stage was that in some samples, the interface between the two textured plates could not be identified with absolute certainty. This was more common in the high speed condition. In most cases, the interface could still be determined with a reasonable level of confidence and the sample was still included in post processing. Figure 4.5 gives an example of one sample where the plate interface is less obvious, but can still be determined with reasonable certainty. An arrow marks the location of the plate interface; it is still characterized by a momentary peak with an area of low amplitude on either side.

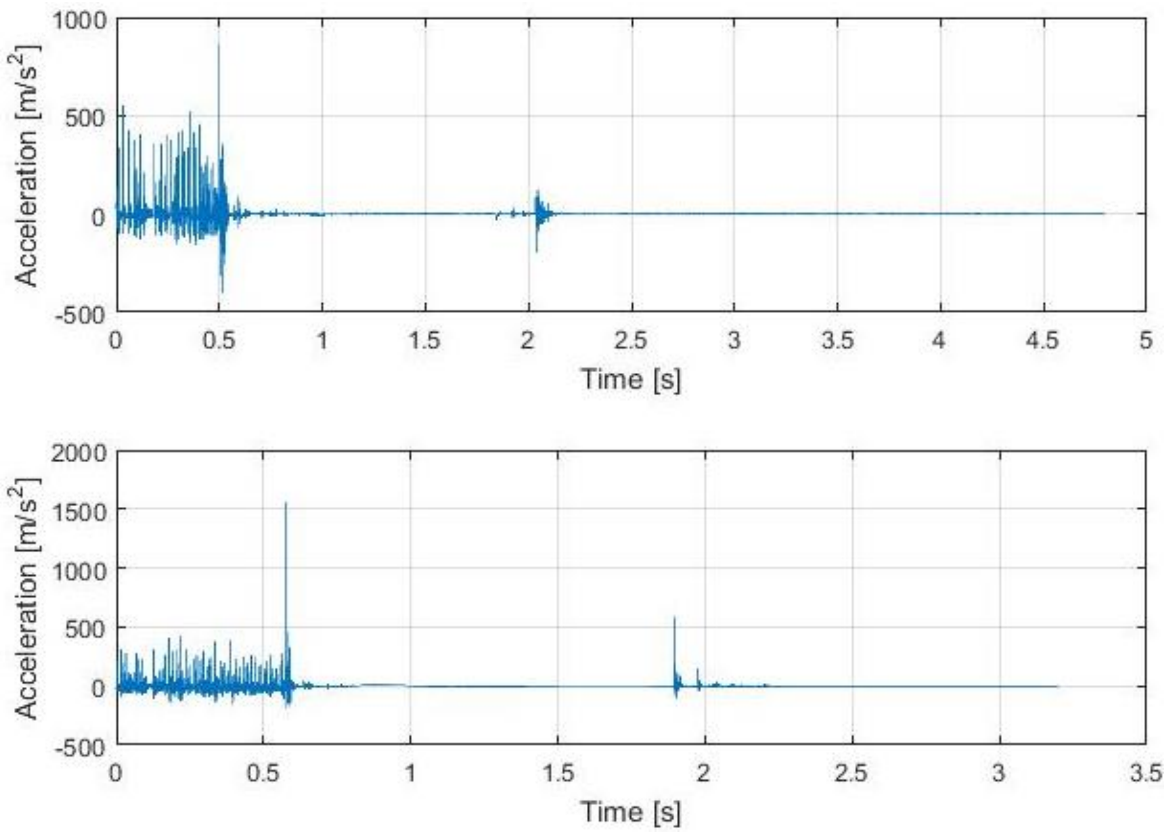

Figure 4.4: Two samples with truncated plate scrape, in high speed condition.

Some samples showed both issues. Figure 4.6 shows a sample where it is not clear where the plate interface happens, and where it seems that part or all of one plate was truncated. These samples were eliminated. Altogether, 1338 samples were used in post processing, out of the 1369 available.

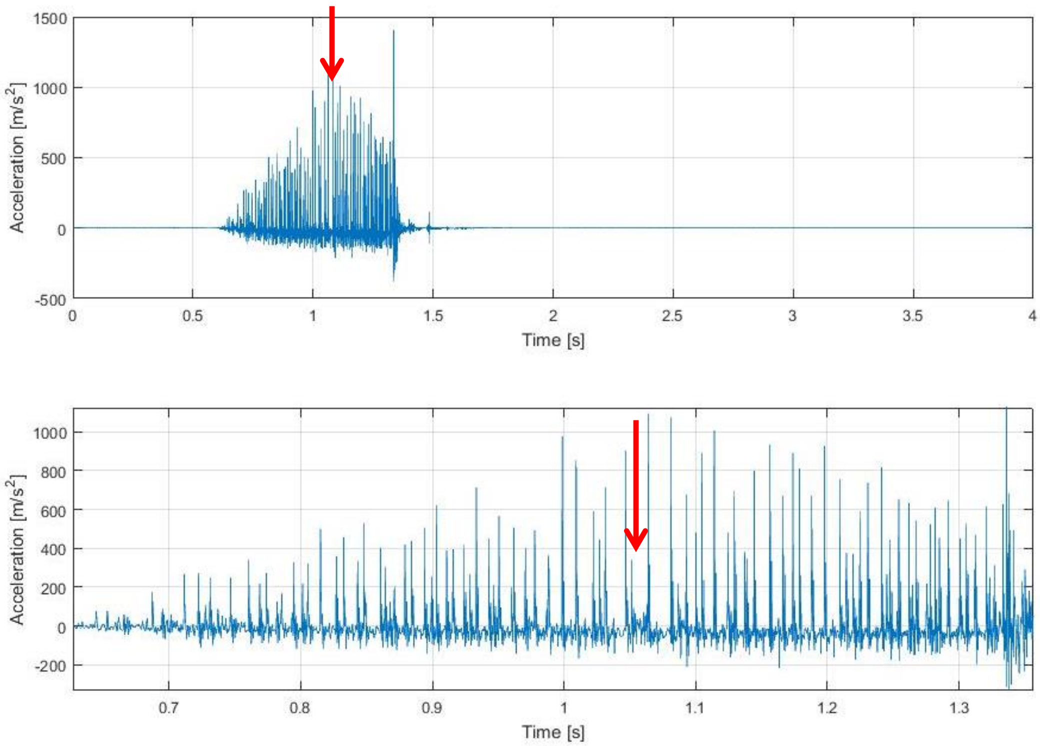

Figure 4.5: Sample showing difficulty in distinguishing interface of textured plates.

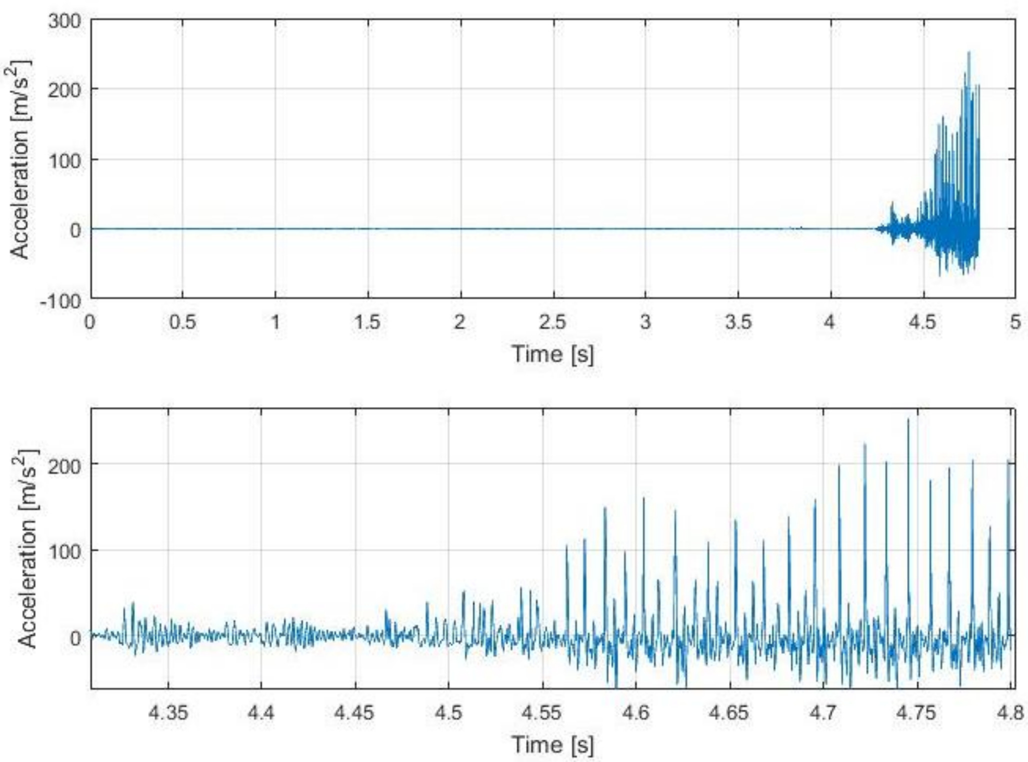

Figure 4.6: Sample showing both truncation and difficult to identify plate interface.

4.3. High-Amplitude Peak Frequency Method

Figure 4.7 shows a small portion of the same trial shown in Figure 4.1 (sample 27 from Table 3.3). This section is on the 5.5 mm plate and just after the cane tip goes over the interface of the two plates. The time record shows a series of regularly spaced, high amplitude peaks, followed by lower amplitude resonance until the next large peak. It appears as if the cane tip is being rhythmically struck as the sample goes on. Figure 4.8 shows part of the 5.5 mm plate.

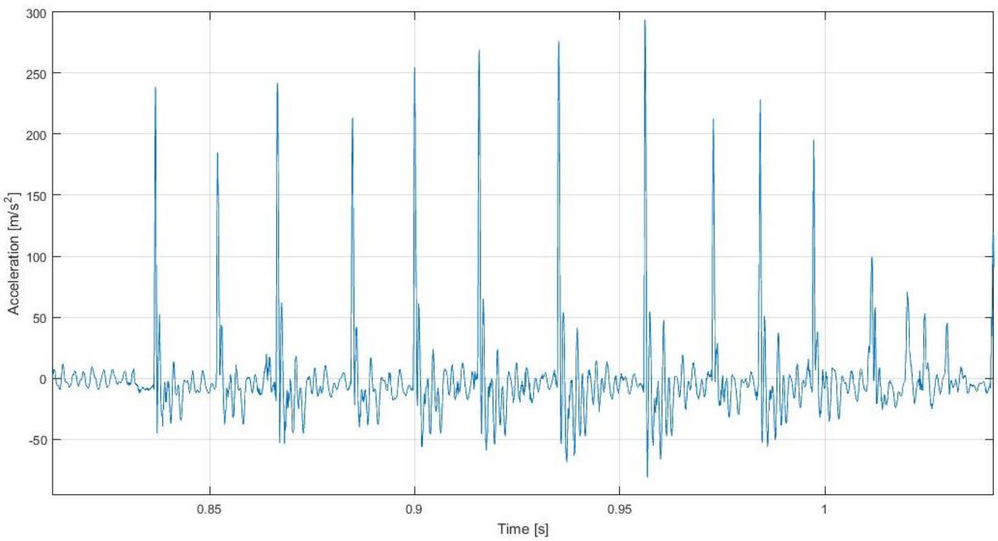

Figure 4.7: Tip accelerometer response from portion of 5.5mm plate in sample 27.

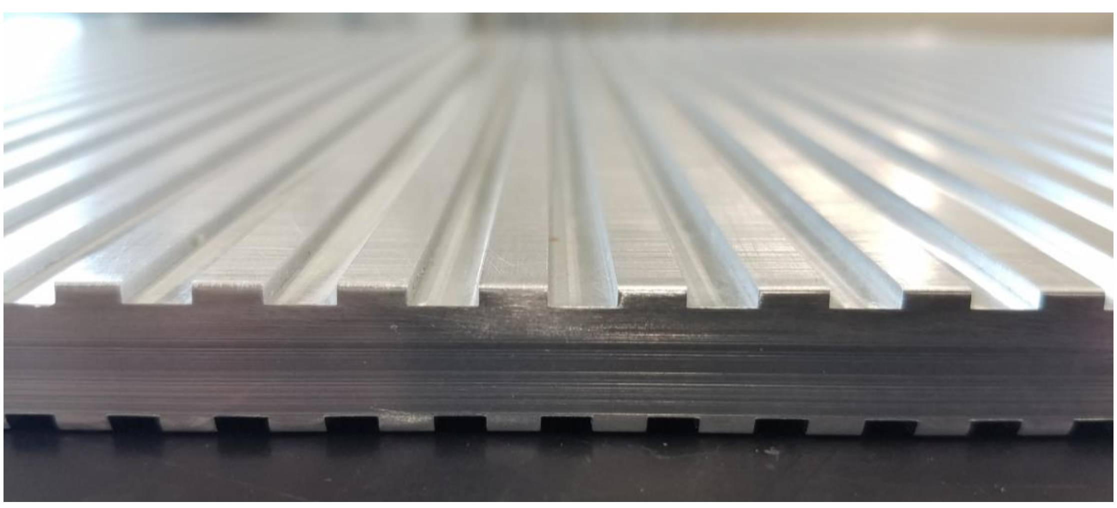

Figure 4.8: The 5.5 mm plate.

Consider Figure 4.7 and Figure 4.8 together. As the cane is dragged from left to right across the plate, the tip slides across one of the flats, then falls into the groove and impacts the leftmost edge of the next flat. The tip is then pulled up onto the next flat, where it falls into the next groove and so on. The regularly spaced, high amplitude peaks in the accelerometer signal are caused by the cane tip falling into the groove and impacting the next edge. It can be shown geometrically that with the cane tip used (the ball tip, radius = 27.5 mm) and the range of groove sizes used in the experiment, that the cane tip is not able to touch the bottom of the groove for any of the surfaces.

When the cane user scrapes across the two plates and makes a decision about which half is rougher, it seems likely that they are paying attention, at least in part, to a change in these high amplitude peaks. Specifically, they are feeling for the plate which has grooves that are spaced further apart, and pay attention to these high amplitude peaks to determine how often the cane tip moves over a groove.

A script was written in MATLAB to identify the peaks in the accelerometer signal that were likely caused by the cane tip falling into a groove in the plate, and use that information to make a selection about the roughness of the two plates. Figure 4.9 shows the same time signal as Figure 4.7, after the peaks have been identified using MATLAB's *findpeaks* command. They are marked with triangles.

The logic here is that if the participant is paying attention to these high amplitude peaks as a cue to the roughness of the two surfaces, we should also be able to make a decision by detecting these peaks in the cane vibration. While the participant may be making a qualitative judgement (which plate “feels” rougher), an algorithm can make a quantitative judgement (which plate is “numerically rougher,” according to some criteria).

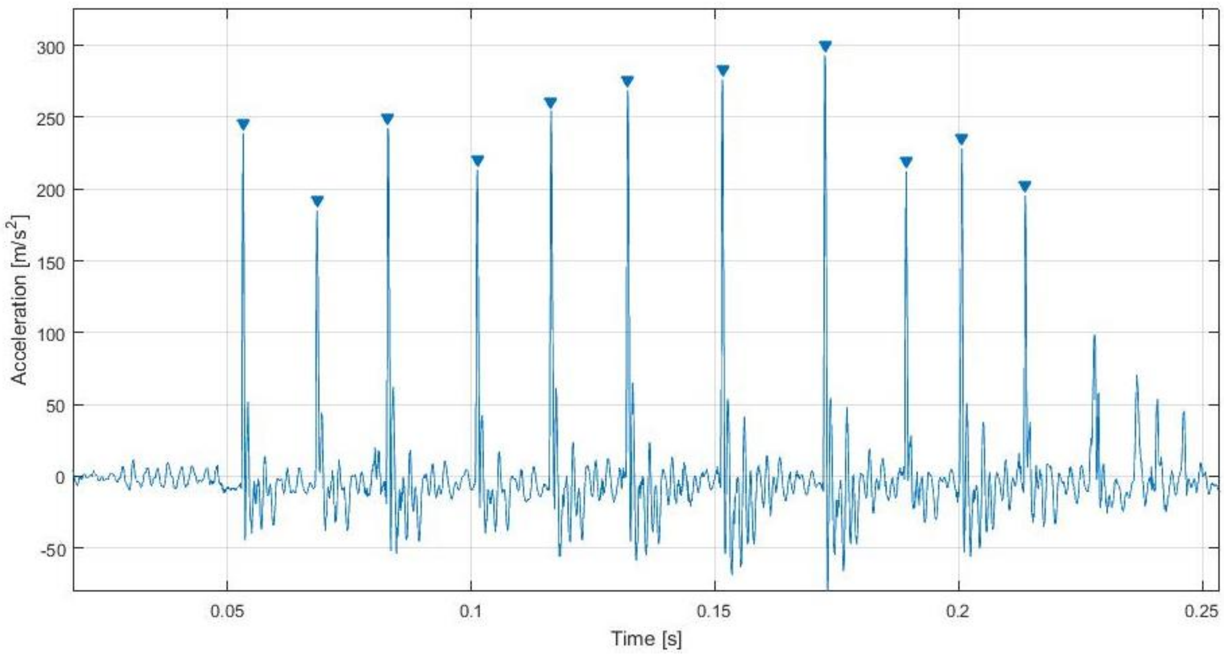

Figure 4.9: The 5.5 mm plate, with peaks identified using MATLAB *findpeaks* command.

The accelerometer data can tell us where peaks happen in time, but there is no information directly recorded about how the cane tip moves in space. Two different methodologies can be used to make a decision about plate roughness using just the time record, but each one requires a simplifying assumption. The first method is to simply use MATLAB to count the number of peaks that occurred during each half of the scrape, and select the plate with fewer peaks as the rougher one. After all, the number of grooves on each plate is already known. This method also seems appealing because it is not sensitive to changes in the velocity of the cane tip; even if one side scraped faster than the other, the number of grooves encountered by the cane tip does not change. This method relies on the assumption that in every trial, the participant scraped the whole length of both surfaces, and that the cane tip remained in contact with the surface at all times.

Unfortunately, this assumption is not representative of many of the samples. As discussed earlier, there are some samples where a part of the scrape is truncated from the recording. Even though a large enough portion remains to estimate the cane vibration on that side, comparing the number of peaks requires that the entirety of every plate is present in the data. Any missing portion will cause an error in the output. The assumption also does not hold for samples where the participant did not physically scrape all of both surfaces. This happened when the participant did not start with the cane tip touching the left edge of the wooden frame as instructed or stopped before touching the right edge, or when the cane tip fell off of the near side of the plate. Some examples were also noted where the cane glided across the plate surface and did not interact with every groove, especially in the high speed condition.

In all of these cases, it is not reasonable to make the assumption that the cane scraped the whole length of both surfaces. Furthermore, it would be difficult to screen the accelerometer responses to eliminate all of the samples for which part of a plate was truncated, because it is hard to visually identify that the whole plate was contacted by looking at the accelerometer output.

The second method to select the rougher plate uses the time history data as a proxy for position, by making the assumption that the average cane swipe speed is the same for both plates. In this method, a MATLAB script counts the number of peaks on one of the surfaces, and divides that by the time elapsed between the first and last peak. This calculates a “peak rate”, which gives a measure of how frequently the cane user felt peaks while scraping that side. The same calculation is performed on the other side as well. If the cane tip is moving at a constant speed across the plate, then the peak rate and groove spacing are related by a constant (velocity). The rougher plate, then, is the one with a lower rate of peaks in the accelerometer output.

It should be clear that this assumption makes a simplification, because the cane tip starts at rest up against the left edge of the first plate. When the participant begins the scrape, the cane tip speeds up, but the velocity variation across the swing is not precisely known. It is likely that the swing speeds up to some rate that is approximately constant, and then slows back down as the cane tip reaches the right edge. Note that it is not assumed that the absolute speed of the cane is constant across the whole swing, nor that the swipe speed is the same from one sample to the next, but only that the average speed on each half of one swipe is about the same.

Consider the case where half of one of the plates is truncated from the sample recording, or where the participant did not scrape over the whole plate with the cane tip. In the first method which only counted the number of peaks, that side would have fewer grooves and so the algorithm would interpret it as being rougher than it really is. By finding the rate of peaks, the number of grooves is lower, but the elapsed time between the first and last peak is also shorter, and the peak rate is not changed. An algorithm was implemented in MATLAB using this method, and it was found to predict which of the two textured surfaces was rougher at the same level that the participants were able to.

4.4. High Amplitude Peak Frequency Implementation

A MATLAB script was written to open the data file corresponding to a sample, find the rate of peaks on the right and left plates, and output a number that indicates how that rate changed from one side to the other. This script is included in Appendix A.

The script begins by loading a list of all the samples that were eliminated because of the conditions outlined earlier, an array of the plate groove sizes used in each sample, an array indicating the response of the participant, and the array generated earlier that contains indices for the beginning, middle and end of every scrape sample in its raw data file. Next, a loop begins that analyzes each scrape one at a time. Beginning with sample 1 from the first participant, the script first checks to see if the sample number is on the list of eliminated samples. If not, it loads the structure that was exported from Smart Office Analyzer and contains the raw vibration data for that sample, saves the section corresponding to the left plate to one variable, and saves the section corresponding to the right plate to another one.

The last 50 milliseconds of the left plate are eliminated from that sample, along with the first 50 milliseconds of the right plate. This is to remove the peak associated with the interface between the two plates. The 50-millisecond time interval was selected by trial and error, and was found to be a reasonable value to eliminate the whole peak, without truncating much of either of the plates. The same time interval was used for the slow and fast conditions because only the single large peak caused by the plate interface needs to be eliminated.

Next, the *findpeaks* MATLAB command is used on each dataset to identify the location of any peaks that exceed a preset threshold. The number of identified peaks on each side is divided by the time difference from the first peak to the last one on that side. This number has units of peaks per second, and the result corresponding to each plate is saved in an array. The script processes every sample in the same way, then the result from the left plate are subtracted from the results from the right plate to give a difference in peak rate. Figure 4.10(a) shows one whole sample, where the left plate is 3.5 mm and the right plate is 5.5 mm. Figure 4.10(b) shows the peaks identified on the left plate, where there are 75 peaks in a time interval of 0.6771 seconds. Figure 4.10(c) shows the peaks identified on the right plate, where there are 61 peaks in 0.8762 seconds.

The peak rates are calculated in peaks per second as

$$rate_{left} = \frac{N_{peaks}}{dt} = \frac{75}{0.6771} = 110.8\ Hz$$

$$rate_{right} = \frac{N_{peaks}}{dt} = \frac{61}{0.8762} = 69.62\ Hz$$

The difference in rate between the two plates is

$$rate_{change} = rate_{right} - rate_{left} = 69.62 - 110.8 = -41.18\ Hz\ .$$

If the difference value for a pair of plates is positive, it means that the high amplitude peaks corresponding to grooves in the textured plates happen more frequently on the second (right) plate than the first (left). With the assumption that both plate scrapes take about the same amount of time, this means that the grooves on the right side are physically closer together, so the left plate is the rougher of the two. If the difference value is negative, as in this example, the grooves happen more frequently on the left plate, so the right is the rougher of the two. The change in groove dimension is calculated by

$$groove_{change} = size_{right} - size_{left} = 5.5mm - 3.5mm = 2.0mm\ .$$

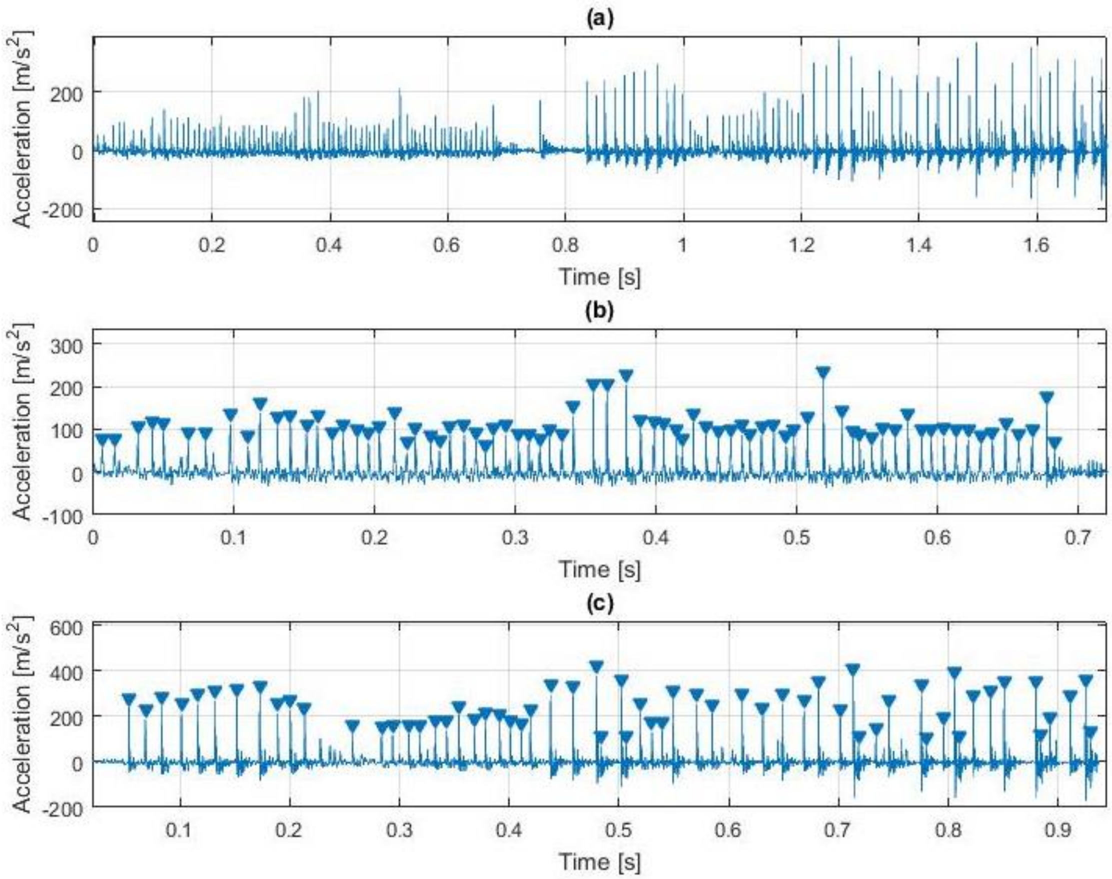

Figure 4.10: (a) Sample accelerometer response, (b) identified peaks in the left plate, and (c) identified peaks in the right plate.

In this example, the calculated peak rate decreased and the plate groove size increased, so the algorithm correctly selected the rougher plate. To score the output of the script, the peak rate difference is multiplied by the change in plate groove size, and the sign of the result is noted. In this example

$$rate_{change} * groove_{change} = (-41.18\ Hz) * (2.0\ mm) = -82.36\ .$$

Correct answers have a negative sign, as in this sample; the peak frequency decreased (-) and the groove size increased (+). The result would also be negative if the peak frequency increased (+) and the groove size decreased (-). The algorithm is incorrect when this result has a positive sign:

the groove size got larger (+) but the peak frequency also increased (+), or the groove size got smaller (-) but the peak frequency also decreased (-).

Figure 4.11 shows another way to visualize the result. Each pair of plates is represented as one point on a scatter plot, where the horizontal axis shows the change in plate groove size from left to right, in millimeters, and the vertical axis shows the change in peak frequency in Hertz. Each band on the horizontal axis represents one pair of plates. For example, the four points at the (+1) coordinate had a 3.5 mm left plate and 4.5 mm right plate. One block condition is shown here (sample 1 – sample 32 from Table 3.3).

Correct identifications are in the second and fourth quadrants, and incorrect identifications are in the first and third quadrants. There seems to be a linear trend relating the change in groove size to the change in peak frequency. This makes sense conceptually; a small change in groove dimension should result in two frequencies that are similar, while a large change in dimension should result in two frequencies that are more different.

The most important part of the algorithm for peak selection is the minimum threshold that is set in the *findpeaks* command. If it is set too high, the command will miss some of the high amplitude peaks caused by grooves in the surface, changing the rate calculation and making the plate seem rougher than it really is. If the threshold is too low, the command will count all of the peaks of interest, and also count peaks that are associated with the resonance of the cane or even electrical noise, making the plate seem smoother. If no threshold is specified at all, the command will count every array element that is higher in magnitude than the ones immediately before or after it.

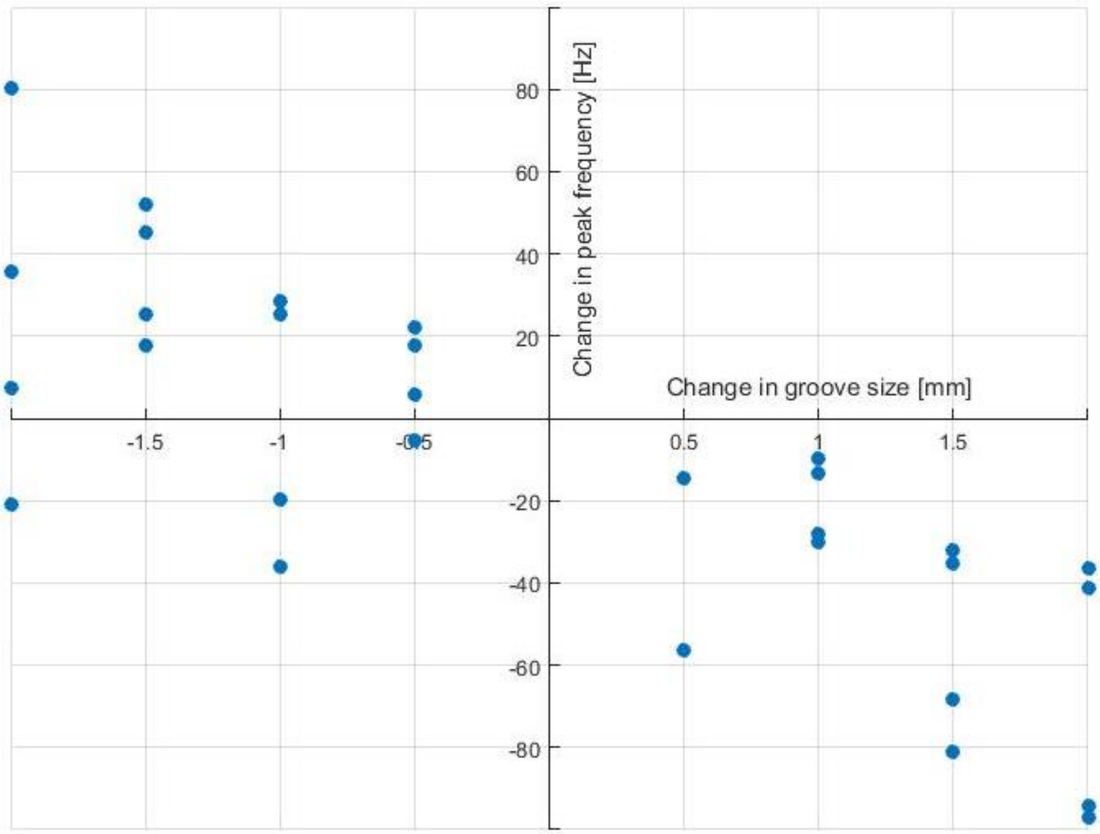

Figure 4.11: Scatter plot of change in peak frequency against change in groove size.

The ideal threshold varies with the amplitude of the peaks in each sample, and this amplitude might change with the cane user, how much downward force the user puts on the cane tip, the speed of the cane swipe, and perhaps the roughness of the surface. In fact, we noted earlier that for the sample shown in Figure 4.10, it seems that the average amplitude is higher for the right plate than the left, so it is unlikely that the ideal threshold level is the same even for both plates in the same sample.

The minimum threshold level was set independently for each of the plates, in every sample. To set the threshold, all the peaks in a sample are identified and sorted from largest to smallest magnitude. The largest peak is thrown out, and then the mean is calculated from the next 10 largest peaks (that is, the ones ranked 2 through 11). The logic of this method is that by averaging the large peaks in a sample, it gives an indication of how large we might expect the rest of the important peaks to be. Using 10 peaks in the average was found to be a reasonable value through trial and error. By using fewer, only unusually large peaks are counted, and the mean is not representative of the rest of the important peaks in the sample. By using many more, especially for shorter samples, the mean might include all of the important peaks and some that were not caused by grooves, so the threshold captures many more peaks than is desired. The largest peak was eliminated to remove other events that could change the average value significantly, such as the cane impacting the far wall of the wooden frame, or falling off of the grooved surface.

Once a mean was calculated from the large peaks in a sample, it was multiplied by some fraction and used as a threshold. The script correctly predicted the rougher surface at the highest rate with when the threshold was set to 40% of the mean; a discussion of how changing this value impacts the results is provided later. The calculated threshold level was used as the required minimum peak prominence, and then *findpeaks* was used on the signal again to find just the peaks in the signal that meet this requirement.

Peak prominence is a value that is slightly different than an absolute magnitude threshold, in that it will not count two peaks that are very close together if there is not a substantial decrease in magnitude between them. A magnitude threshold will result in the function picking every point that is higher than the threshold, and higher than its two neighbors. This may result in several peaks being identified in close proximity, when they were all likely caused by the same event. Instead, prominence measures how much a peak stands out compared to the ones around it. The prominence calculation finds the amplitude of a peak, looks for the closest point on each side that reaches the same magnitude, and then finds the minimum value in the data within the interval on each side. The higher of the two minima is set as the reference level, and the prominence is the height of the peak above this reference. In other words, it measures how tall a peak is, compared only to other peaks of similar size.

4.5. High Amplitude Peak Frequency Results

Out of 1338 samples that had satisfactory vibration recordings, the subjects correctly identified the rougher surface 1078 times. The high amplitude peak frequency algorithm correctly identified the rougher surface 1072 times when using a peak prominence of 40 percent of the calculated mean peak value. Table 4.1 compares the detection performance between the participants and the peak frequency MATLAB algorithm by block condition, Table 4.2 compares performance by the change in plate dimension between the left and right sides, and Table 4.3 compares detection performance by block condition, for each of the 11 participants individually.

When compared to the participant results, the peak frequency method is equally effective in the two low speed conditions. It performed slightly better than the participants with the flexible cane at high speed, and slightly more poorly with the rigid cane at high speed. The algorithm performed better than the participants at the smallest groove size change (0.5 mm) and equally well for the 1.0 mm size change. The participants performed better when the change in groove size was large (1.5 mm or 2.0 mm). This may be because the participants felt not just a vibration change, but also a proprioceptive change between the two surfaces.

Performing a paired t-test on the participant and MATLAB detection values in Table 4.3 finds that there is no significant difference in detection between the two methods ($n = 44$, $t = 0.45$, $p = 0.656$). That is, by identifying the high amplitude peaks in the accelerometer output and comparing how frequently they occur, a script was able to determine which plate was rougher as well as the human participants.

Table 4.1: Correct roughness identification, by block condition.

Block Condition	Number of Samples	Number correctly identified - Participant	Number correctly identified - Algorithm
Rigid Low Speed	341	281	281
Rigid High Speed	322	247	240
Flexible Low Speed	343	293	291
Flexible High Speed	332	257	260
All Conditions	1338	1078	1072

Table 4.2: Correct roughness identification, by change in groove dimension.

Change in plate groove dimension	Number of Samples	Number correctly identified - Participant	Number correctly identified - Algorithm
± 0.5 mm	333	217	238
± 1.0 mm	334	238	237
± 1.5 mm	332	302	289
± 2.0 mm	339	321	308
All Conditions	1338	1078	1072

Performing an ANOVA analysis to determine the effect of cane rigidity and swipe speed on the correct or incorrect scoring of the algorithm shows that the peak frequency method identifies the rougher plate significantly better in the low speed condition ($F = 10.95$, $DF = 1$, $p = 0.001$), but performs equally for both the rigid and flexible canes ($F = 2.04$, $DF = 1$, $p = 0.153$). The interaction between swing speed and cane rigidity is not significant ($F = 0.10$, $DF = 1$, $p = 0.757$). This is the same trend that was noted for the participant performance. Both the participants and the peak frequency method perform better in the low speed condition but equally well with each cane. This may indicate that the participants are paying at least some attention to the large amplitude peaks caused by the plate grooves when making a decision about which plate is rougher. Both the participants and algorithm are more accurate when the large amplitude peaks are distinctly different, and both are less accurate when the peaks are more similar.

Table 4.3: Correct roughness identification, by participant and block condition.

Participant	Block Condition	Number of Samples	Number correct – Participant	Number correct – Algorithm
1	Slow Rigid	30	25	26
1	Slow Flexible	30	25	23
1	Fast Rigid	30	24	22
1	Fast Flexible	30	25	25
2	Slow Rigid	30	24	24
2	Slow Flexible	31	27	26
2	Fast Rigid	31	24	27
2	Fast Flexible	30	23	25
3	Slow Rigid	32	25	28
3	Slow Flexible	32	28	26
3	Fast Rigid	26	19	19
3	Fast Flexible	30	17	20
4	Slow Rigid	31	26	27
4	Slow Flexible	32	29	28
4	Fast Rigid	30	19	23
4	Fast Flexible	31	28	28
5	Slow Rigid	31	25	27
5	Slow Flexible	32	26	28
5	Fast Rigid	25	16	18
5	Fast Flexible	32	23	23
6	Slow Rigid	31	24	24
6	Slow Flexible	32	27	28
6	Fast Rigid	31	27	23
6	Fast Flexible	32	25	24
7	Slow Rigid	31	25	24
7	Slow Flexible	30	26	29
7	Fast Rigid	30	23	24
7	Fast Flexible	30	25	24
8	Slow Rigid	32	27	25
8	Slow Flexible	32	28	28
8	Fast Rigid	32	24	20
8	Fast Flexible	31	23	25
9	Slow Rigid	31	26	26
9	Slow Flexible	32	28	28
9	Fast Rigid	29	21	17
9	Fast Flexible	27	23	22
10	Slow Rigid	32	28	26
10	Slow Flexible	29	26	26
10	Fast Rigid	28	23	22
10	Fast Flexible	32	23	25
11	Slow Rigid	30	26	24
11	Slow Flexible	31	23	21
11	Fast Rigid	30	27	25
11	Fast Flexible	27	22	19

4.6.	Vibration Amplitude Method

It was suggested that when a user feels the texture of a surface using a probe (like a white cane), he or she interprets the surface as being rougher as the vibration amplitude of the probe increases [24], [26]. In that case, the participants may also be paying attention to the amplitude of vibration (or change in amplitude) when selecting the rougher textured surface. The MATLAB script used for peak frequency measurement was modified to also compare the amplitude of large peaks between each side of the scrape. Refer to Figure 4.1 for reference, which shows the tip accelerometer response for one scrape sample, and is included again here.

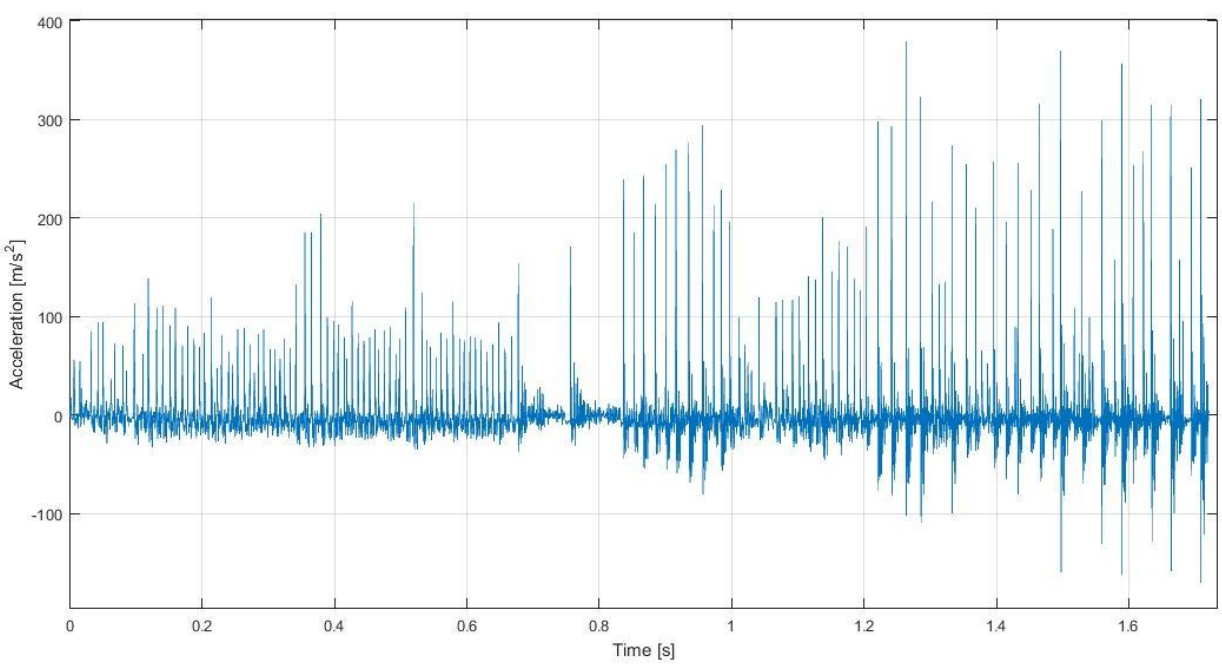

Figure 4.1: Tip accelerometer response for Sample 27 in rigid low speed condition.

There are several ways that the amplitude of the vibration response between the two plates could be compared. The simplest to implement is to use one of the numbers that was already calculated: the average amplitude of peaks 2 through 11 for each side, or the minimum prominence threshold for each side (remember, the two values are related by a constant). This amplitude measurement was developed to gauge the average amplitude of the peaks that were directly caused by interaction between the cane tip and plate grooves, so it may a useful number to use when comparing two plates together.

The average amplitude of all the peaks in the signal could be compared. As discussed earlier, however, if there is no minimum threshold set in MATLAB's *findpeaks* command, it will consider every array value that is larger than the values directly before and after it. This will include low amplitude peaks caused by the cane resonance and even electrical noise, and not just the high amplitude vibration directly caused by the textured surface, so it is not a good indication of the amplitude of excitation from the surface.

The root mean square (RMS) value of the signals could be compared as well, as a measure of the average amplitude of the entire signal corresponding to each plate, although this method turned out to be a poor predictor of which plate was rougher when it was implemented. The high amplitude peaks in the vibration seem like the most prominent part of the signal, however, these peaks are very short in duration (on the order of 1 millisecond). Because of this, the RMS of the signal trends much more closely to the average amplitude of the cane resonance than to the average height of the large peaks.

To make a decision about which plate is rougher using the relative amplitude of the two signals, the MATLAB peak frequency script was modified to save the calculated mean amplitude level from the largest peaks corresponding to each plate in the sample, and then subtract the left value from the right one. This gives a figure measuring the difference in acceleration amplitude, in meters per second squared. It would be expected that this value is positive if the right plate is rougher and negative if the left plate is rougher. To score the result, the amplitude difference is multiplied by the plate groove dimension change. Positive values of the result indicate correct identification, and negative values indicate incorrect identification. Figure 4.12 shows a scatter plot for one participant in the rigid low speed condition (sample 1 – sample 32 from Table 3.3).

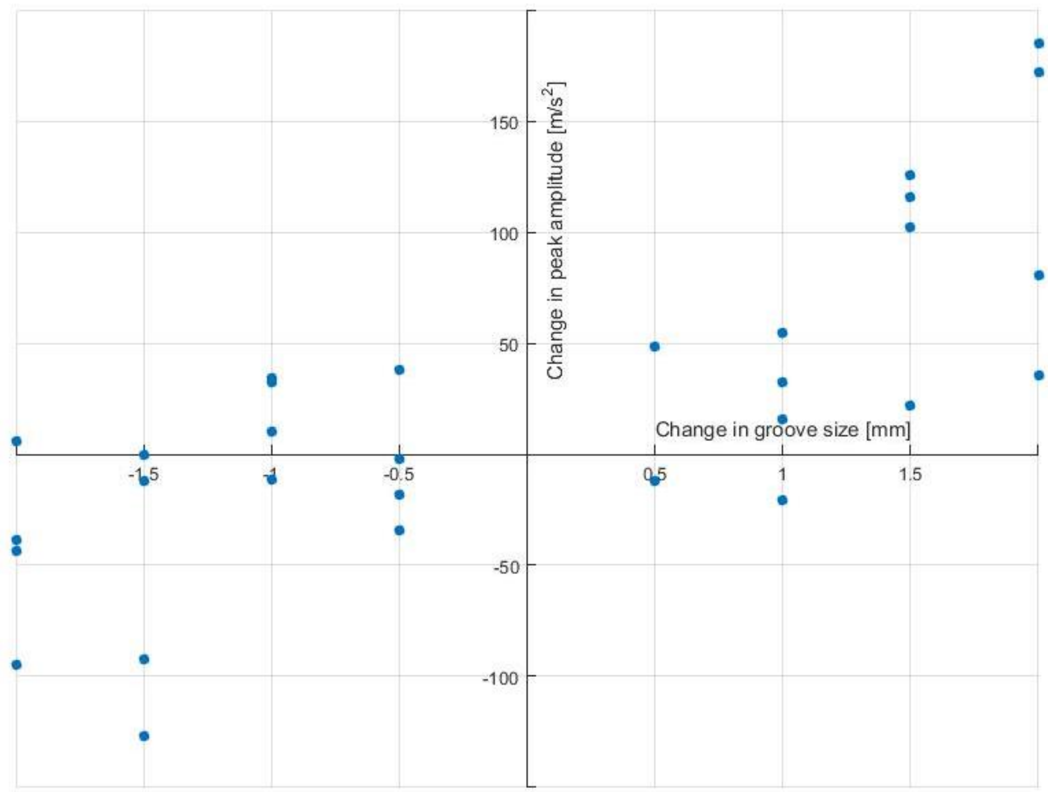

Figure 4.12: Scatter plot of change in peak amplitude against change in groove size for rigid low speed condition.

This time, points that fall in the first or third quadrant are correct, and points in the second or fourth quadrant are incorrect. This is because an increase in plate dimension (rougher) should correspond to an increase in vibration amplitude, and a decrease in plate dimension (smoother) should correspond to a decrease in vibration amplitude.

Consider Figure 4.13, which compares the groove dimension change to peak amplitude change, but this time for a block of high speed samples (sample 33 – sample 64 from Table 3.3, rigid high speed condition). There is still a trend from bottom left to top right in the figure, but this time nearly all of the values are positive. This means that for all the samples in this block but the three located in the third quadrant, the right plate created higher amplitude peaks, even if it was the smoother plate. This effect is noticeable in the high speed conditions both canes, for all 11 participants.

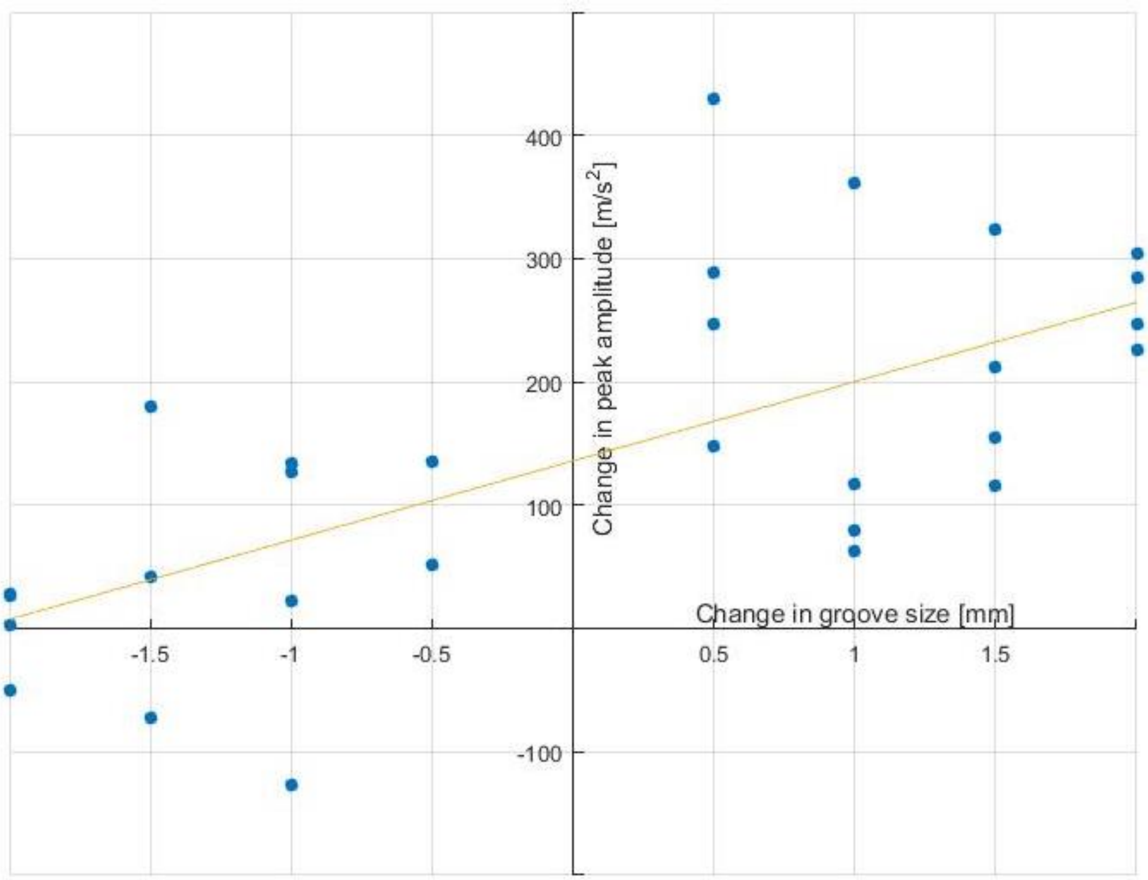

Figure 4.13: Scatter plot comparing change in peak amplitude to change in groove size for rigid high speed condition.

It is not clear why the vibration amplitude tends to be higher on the right side. In every sample, the participant began on the left and scraped to the right. It could be that the scrape speed and cane momentum tends to increase as the cane is swiped, contrary to our earlier assumption, and so the cane tip is moving faster when it impacts the grooves on the right plate. All 11 participants were also right handed, so it could be that the participants tend to put more downward force on the cane when on the right side of the swipe. It may be that the actual impact force is not changing, but that the cane tilt angle is decreasing across the swipe (the angle the cane makes with the ground), such that the accelerometer at the tip is more horizontal and so reads the true tip acceleration more closely. This cause in particular seems unlikely because, as discussed earlier, the cane tilt angle varies by only a few degrees while the cane is in use [19]. Whatever the source of this effect, it may be more prominent at high speed because the participant is not as controlled or deliberate in his or her swing.

If some effect is present that increases the vibration amplitude on the right side of the swing, then the sign of the change in amplitude cannot be used to identify the rougher plate, as all (or nearly all) of the samples carry the same sign. However, if the size of this effect could be identified, it could be subtracted from the amplitude change that is calculated for each sample, and it may still be possible to select the rougher plate using the amplitude of the cane's vibration.

In order to try and remove the magnitude of this unknown effect, the amplitude difference was calculated for every sample, and then results were grouped by participant and by block condition, so that there were 44 sets of data (11 subjects, with four conditions each). A least-squares linear regression was fit to each set of data with the MATLAB "polyfit" command, and the calculated y-intercept β_0 was subtracted from each data point in the set. The y-intercept is used as an estimation of the effect size that leads to increased vibration amplitude on the right side of the cane swipe. A separate y-intercept was calculated for each participant in each of the four block conditions, because it seems likely that this effect may change with participant, swing speed or cane rigidity.

Figure 4.14 shows the same data set as Figure 4.13, with the best-fit y-intercept (135.97 m/s^2) subtracted from each sample. This data set looks more like what was expected, where moving to a rougher plate increases the vibration amplitude, and moving to a smoother plate decreases it. What we are really saying is that moving to a rougher plate increases the vibration amplitude "more than expected," while moving to a smoother plate increases the vibration amplitude "less than expected." Of course, care should be taken going forward, because we have made the assumption that the unknown amplitude effect is the same for all of the samples taken in a block condition for each participant. This may not truly be the case, it is a simplification.

4.7. Vibration Amplitude Results

Out of 1338 samples, the subjects correctly identified the rougher surface 1078 times. The vibration amplitude algorithm correctly identified the rougher surface 1057 times. Table 4.4 shows the correct identification performance between the participants and the vibration amplitude method by block condition (cane rigidity and swipe speed), Table 4.5 compares performance by the change in plate dimension between the left and right sides, and Table 4.6 shows detection performance by block condition for each of the 11 participants. All three also show the number correctly identified using the peak frequency method, for comparison. Table 4.6 also includes the y-intercept β_0 that was subtracted from each sample result in that block condition. Note that the y-intercept is positive for every block, regardless of the cane swing speed. It seems that the unknown amplitude effect is present in the low speed condition as well, even if it is not large enough to be noticed on a scatter plot.

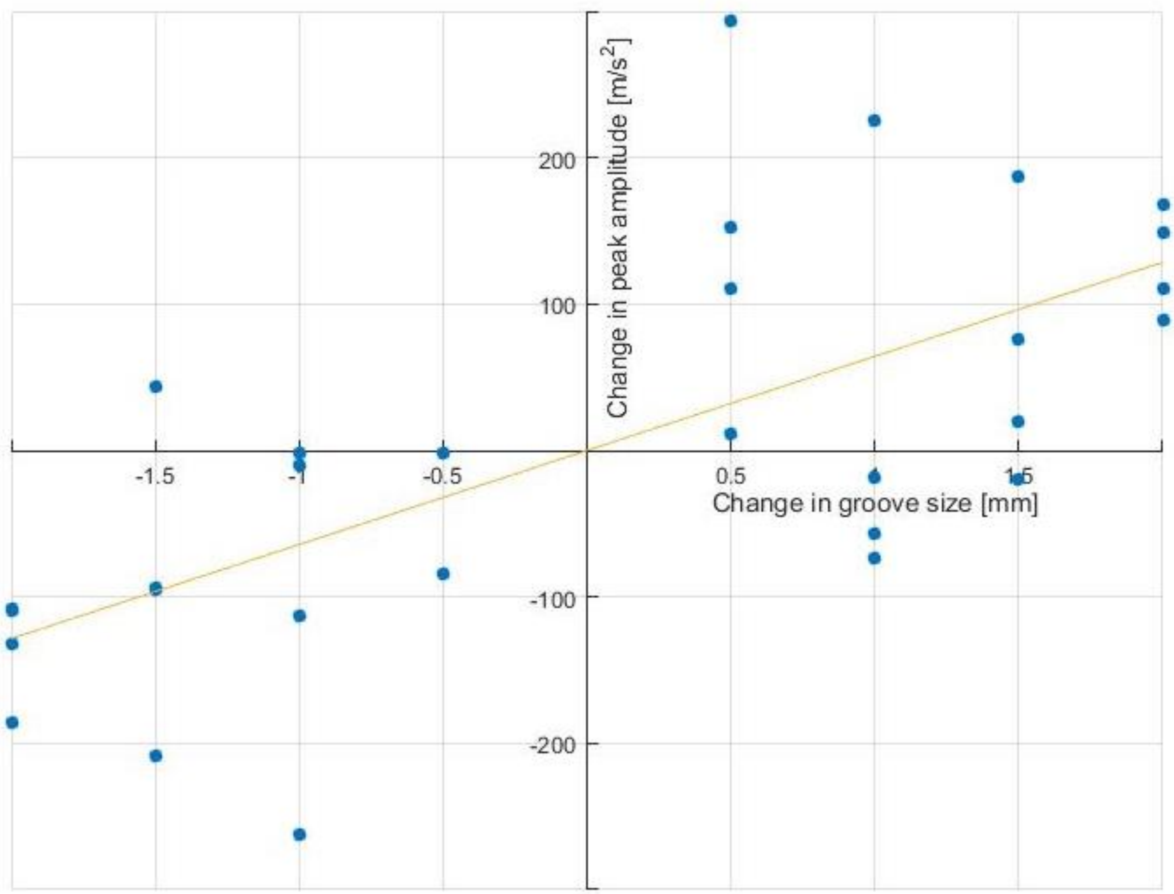

Figure 4.14: Scatter plot comparing change in peak amplitude to change in plate dimension, with y-intercept of linear best fit removed from each point.

The peak amplitude method performed equally well in the rigid low speed condition, when compared to both the participants and the peak frequency method, and better than both in the rigid high speed condition. However, it did not perform as well as the participants or the peak frequency method for either of the conditions using the flexible cane. The peak amplitude method distinguished the smallest groove dimension change (0.5 mm) better than the participants and the largest change (2.0 mm) about as well. It did slightly worse for the 1.0 mm and 1.5 mm groove size changes.

Table 4.4: Vibration amplitude method detection performance, by block condition.

Block Condition	Number of Samples	Number correct - Subject	Number correct – Peak Frequency	Number correct – Vibration Amplitude
Rigid Low Speed	341	281	281	283
Rigid High Speed	322	247	240	253
Flexible Low Speed	343	293	291	277
Flexible High Speed	332	257	260	244
All Conditions	1338	1078	1072	1057

Table 4.5: Vibration amplitude method detection performance, by change in plate dimension.

Change in plate groove dimension	Number of Samples	Number correct - Subject	Number correct – Peak Frequency	Number correct – Vibration Amplitude
± 0.5 mm	333	217	238	232
± 1.0 mm	334	238	237	217
± 1.5 mm	332	302	289	292
± 2.0 mm	339	321	308	316
All Conditions	1338	1078	1072	1057

A paired t-test shows that there is not a significant difference in detection rate between the participant and vibration amplitude method as shown in Table 4.6 ($n = 44$, $t = 1.25$, $p = 0.217$), nor is there a significant difference in detection rate between the vibration amplitude and peak frequency methods ($n = 44$, $t = 0.93$, $p = 0.359$). That is, the peak frequency and peak amplitude methods both use the cane vibration response to identify the rougher of two surfaces with the same success rate as the cane users.

Performing an ANOVA analysis to determine the effect of cane rigidity and swipe speed on the correct or incorrect scoring of the algorithm shows that the peak amplitude method identifies the rougher plate significantly better in the low speed condition ($F = 0.019$, $DF = 1$, $p = 0.019$). It performs equally for both the rigid and flexible cane ($F = 3.67$, $DF = 1$, $p = 0.056$), although the difference is nearly significant with the rigid cane performing better. The interaction between swing speed and cane rigidity is not significant ($F = 0.42$, $DF = 1$, $p = 0.517$). Again, this result mirrors the performance of both the participants and the peak frequency method, in that they perform better in the low speed condition, but equally well with each cane.

This makes sense logically. If the participants are paying attention to vibratory cues to decide which plate is rougher and they perform better at low speed but equally well with both canes, and if the MATLAB script is identifying these same vibratory cues, then we should expect the script to also perform better in the low speed condition and equally well for both canes. In cases where the vibratory cues are distinctly different between the plates, both the participant and algorithm perform well, while in cases where the vibratory cues are more obscured, both the participant and algorithm perform more poorly.

Table 4.6: Vibration amplitude method detection performance, by participant and block condition.

Participant	Block Condition	Number of Samples	Number correct Subject	Number correct Peak Frequency	Number correct Vibration Amplitude	Offset β_0 subtracted from samples [m/s^2]
1	Slow Rigid	30	25	26	24	21.34
1	Slow Flexible	30	25	23	25	135.97
1	Fast Rigid	30	24	22	23	38.30
1	Fast Flexible	30	25	25	22	219.56
2	Slow Rigid	30	24	24	23	264.80
2	Slow Flexible	31	27	26	23	111.18
2	Fast Rigid	31	24	27	26	358.53
2	Fast Flexible	30	23	25	25	68.53
3	Slow Rigid	32	25	28	28	43.87
3	Slow Flexible	32	28	26	25	137.54
3	Fast Rigid	26	19	19	21	38.35
3	Fast Flexible	30	17	20	20	81.97
4	Slow Rigid	31	26	27	27	139.72
4	Slow Flexible	32	29	28	26	16.55
4	Fast Rigid	30	19	23	23	70.70
4	Fast Flexible	31	28	28	23	57.19
5	Slow Rigid	31	25	27	23	16.55
5	Slow Flexible	32	26	28	27	23.80
5	Fast Rigid	25	16	18	18	33.17
5	Fast Flexible	32	23	23	21	103.79
6	Slow Rigid	31	24	24	26	115.90
6	Slow Flexible	32	27	28	26	76.43
6	Fast Rigid	31	27	23	25	198.21
6	Fast Flexible	32	25	24	20	48.42
7	Slow Rigid	31	25	24	24	28.94
7	Slow Flexible	30	26	29	24	52.65
7	Fast Rigid	30	23	24	23	42.74
7	Fast Flexible	30	25	24	23	70.29
8	Slow Rigid	32	27	25	29	95.59
8	Slow Flexible	32	28	28	26	11.17
8	Fast Rigid	32	24	20	26	76.60
8	Fast Flexible	31	23	25	25	24.32
9	Slow Rigid	31	26	26	27	35.23
9	Slow Flexible	32	28	28	31	91.24
9	Fast Rigid	29	21	17	20	70.59
9	Fast Flexible	27	23	22	22	99.53
10	Slow Rigid	32	28	26	28	84.51
10	Slow Flexible	29	26	26	21	24.71
10	Fast Rigid	28	23	22	22	87.73
10	Fast Flexible	32	23	25	27	22.86
11	Slow Rigid	30	26	24	24	79.16
11	Slow Flexible	31	23	21	23	141.17
11	Fast Rigid	30	27	25	26	30.03
11	Fast Flexible	27	22	19	16	96.57

4.8. Discrepancies

The peak frequency and peak amplitude methods both identify the rougher plate as often as the participants in the study do. However, they are not correct or incorrect for all of the same samples. For example, although the participants and peak frequency method identified 1078 and 1072 samples correctly, respectively, they only agreed on 923 of those. The participants identified 158 samples correctly that the algorithm got wrong, while the algorithm identified 148 samples correctly that the participants got wrong. The peak amplitude method was correct in 1057 samples, 929 of which were also correctly identified by the participant; there were 149 samples where the participant was correct but the peak amplitude method was not, and 128 samples where the peak amplitude method was correct but the participant was not. There were 70 samples the participant identified correctly while both MATLAB methods identified incorrectly, and 96 samples the participant identified incorrectly while both MATLAB scripts were correct.

In the ideal case, the algorithms would correctly identify every sample where the participant was correct. By examining the samples where there is a discrepancy between the participant response and the algorithm selection, it may be possible to improve the MATLAB algorithm and reach a higher detection rate. Six causes were identified as common reasons that the algorithm and participant disagree. Broadly speaking, the first is an effect of the experimental design, the next two are caused by unexpected participant behavior, and the last three are due to the nature of the raw data in the sample or the algorithm's method.

First, recall that the experimental design requires the participant to make a decision about which plate is rougher, whether or not they can tell a difference between them. Even if the two plates are indistinguishably similar, the participant must make a guess and will be correct 50% of the time. There is no way to know which correct responses were due to a sufficiently different cane vibration, and which were due to a correct guess despite the plates feeling indistinguishably similar.

Even when the vibration of the two plates is very similar, the MATLAB script will still make a selection about which was rougher. In a sense, the script is "making a guess," in much the same way that the participant did. One might expect the script to be able to find a small quantitative difference and select the right plate, even if the vibration from both plates was too similar for the participant to notice. However, the peak frequency and peak amplitude methods both made simplifying assumptions about the nature of the vibration (namely, that the cane tip moves at the same average speed across both halves, and that the effect causing increased amplitude on the right side was corrected for appropriately). Both methods are approximations of the ways in which the vibration response changed between surface textures, and while the approximations may not affect the algorithm's selection when the vibration is substantially different, it should not be surprising that the algorithm sometimes "guesses" the wrong plate when the vibration is similar. Figure 4.15 shows three samples that were correctly identified by the participant but incorrectly identified by both MATLAB algorithms. Figure 4.16 shows three samples that were identified correctly by both vibration methods, but identified incorrectly by the participant. In all the samples shown, the accelerometer output looks similar for the left and right plates, but the participant and MATLAB "guessed" differently.

There are several samples that were incorrectly identified by the MATLAB script because the plate scrape was somehow unusual. Figure 4.17 shows an effect that happened occasionally in the high speed condition, where it seems that the cane tip bounced along the right plate instead of smoothly dragging across it.

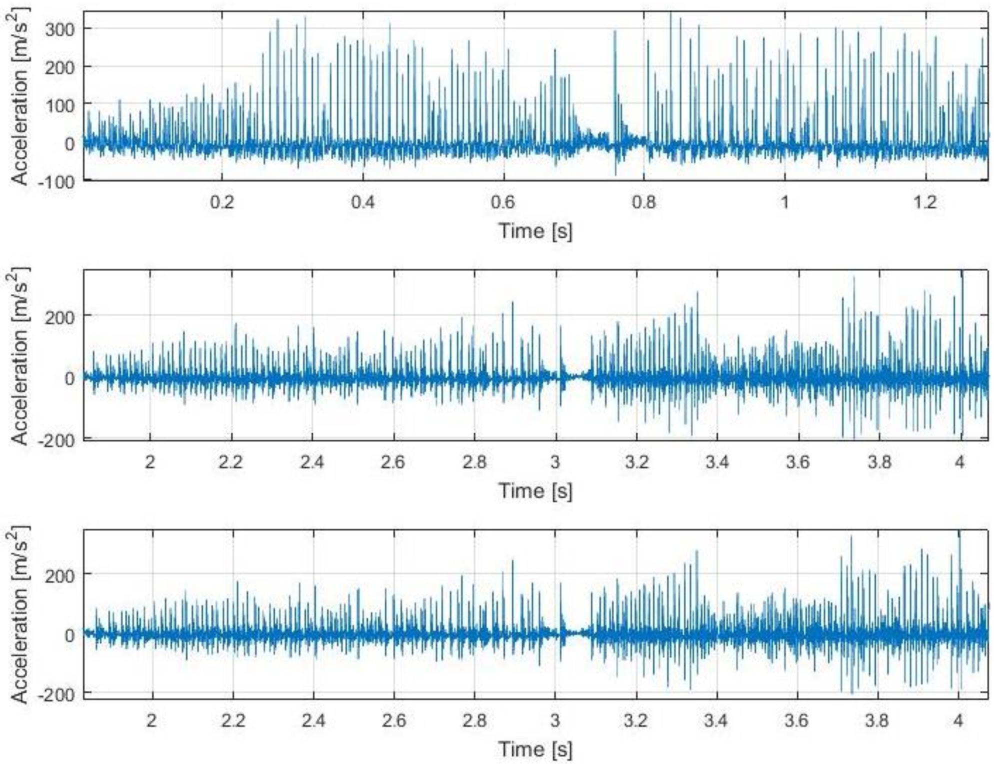

Figure 4.15: Three samples identified correctly by participant, but incorrectly in MATLAB.

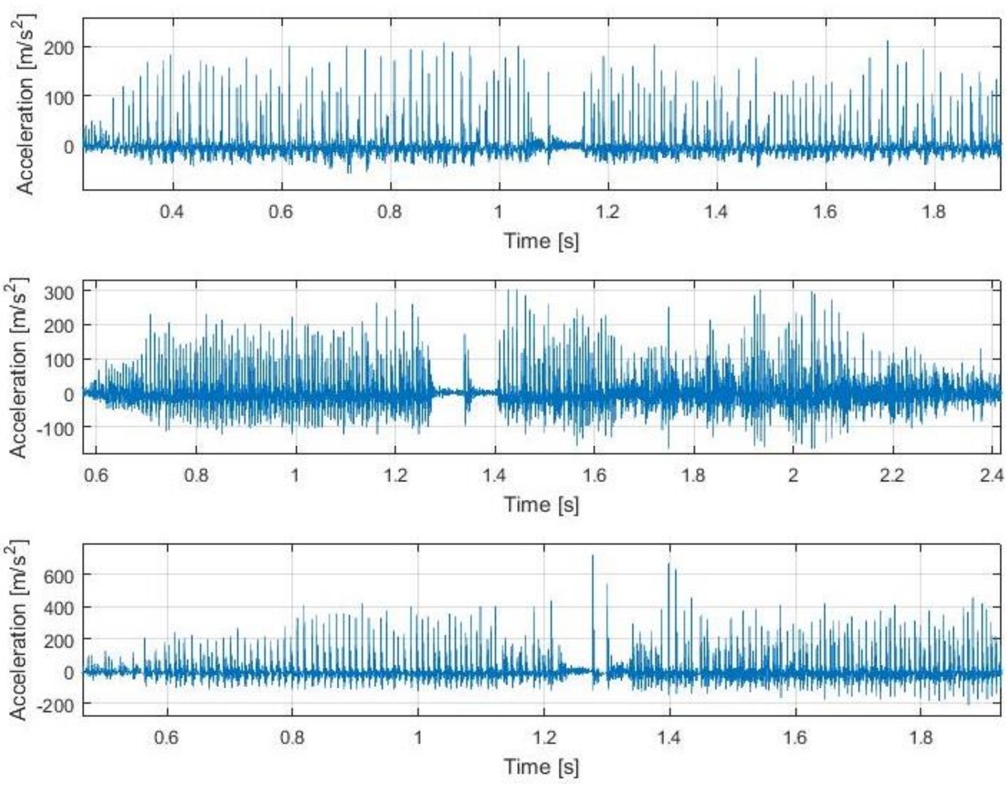

Figure 4.16: Three samples identified correctly in MATLAB, but incorrectly by participant.

The first portion of the scrape looks fairly well controlled, but by about 0.3 seconds the peaks become larger and spaced further apart. In this sample, the rougher plate (4.0 mm) is on the left, and the difference in plate dimension is the smallest increment used (0.5 mm), although one might guess that the rougher plate is on the right by looking at the figure. It seems that the cane tip skipped or bounced along the plate surface in the later part of the scrape, rather than dragging across all the grooves evenly. To prevent this issue in future data collection sessions, the high speed condition could be slowed down to give the cane user more control. Deliberate coaching could also be provided to the participant, to keep the tip of the cane in contact with the plate surface as much as possible.

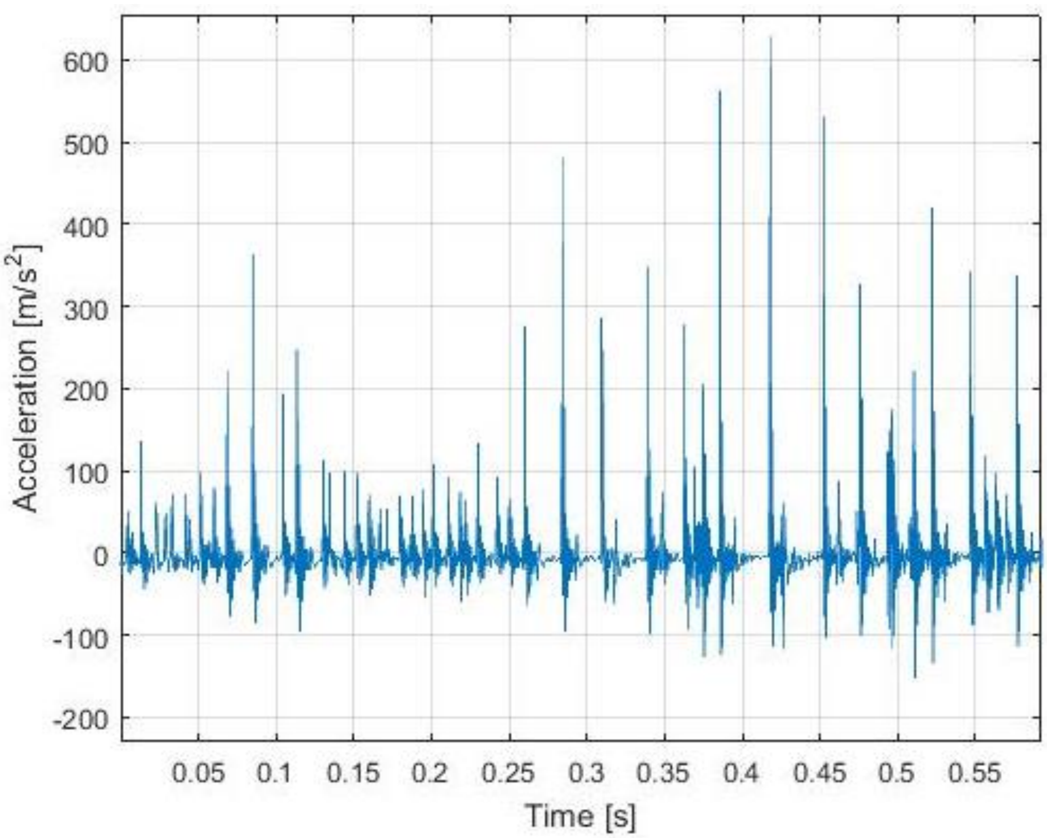

Figure 4.17: High speed sample that shows the cane tip skipping across the right plate.

In some other samples, it seems that the participant was holding the cane inconsistently between trials, such that the accelerometers were not on top of the cane for every sample. Figure 4.18 shows two examples where it appears that the cane was rotated in the hand, so that the accelerometers were on the bottom side. The accelerometer response does not look unusual, except that the large amplitude peaks point in the negative direction. The algorithm in MATLAB does not handle these situations well, because it was written to find high amplitude peaks in the positive direction. For these two samples, it is possible to multiply the response by negative one and analyze it as any other sample. This does not solve the issue, however, when the cane is rotated so that the accelerometers are at some other angle to the ground, as when the cane is rotated 90 degrees, so that the acceleration is measured laterally (right and left) and not vertically.

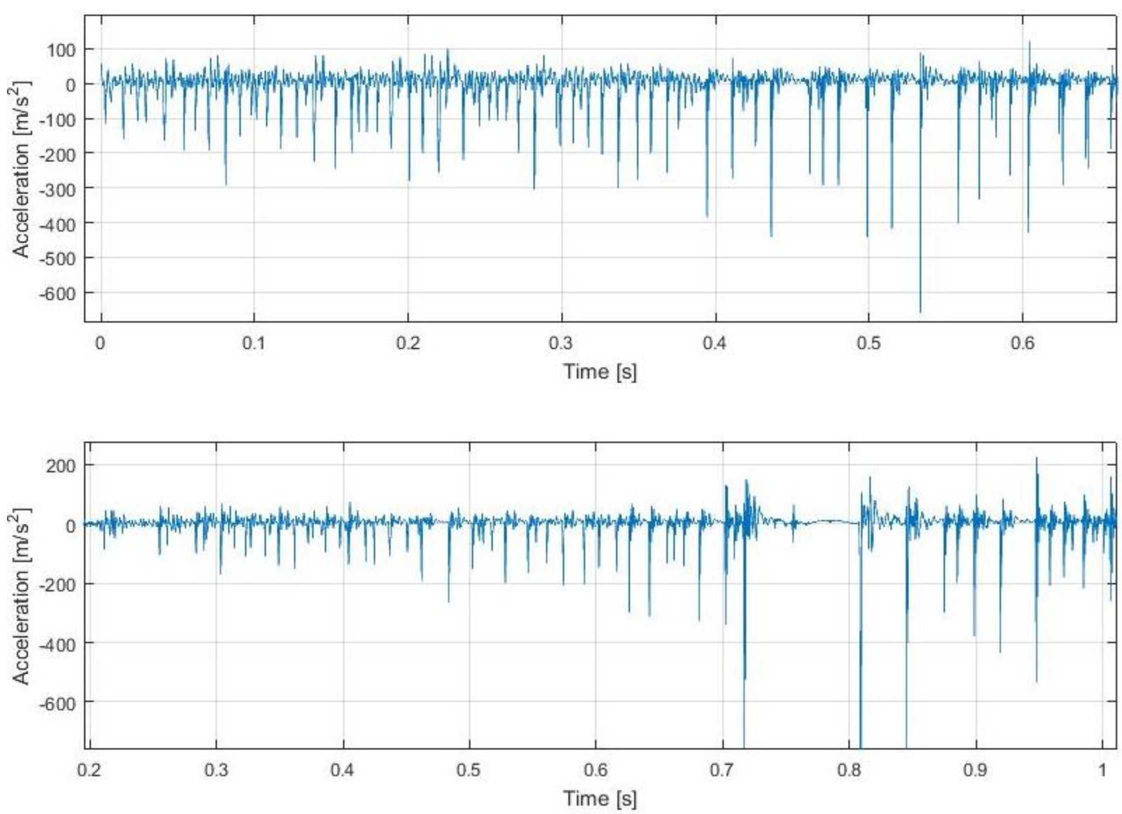

Figure 4.18: Two samples where the participant held the cane upside down, so that accelerometers were on the bottom.

White canes typically have a flat section on one side of the handle that the user places his or her pointer finger on, and the accelerometers were mounted so that they would be on top of the cane when it was held in this way. Participants in this study were coached to keep the cane in that orientation, but it seems that in a few cases they did not. Again, this issue can be prevented in the future by deliberately coaching the participants with regard to cane position, and paying attention to correct the cane roll angle when necessary.

The next two issues that were noted several times deal with the way in which the required amplitude threshold to count a peak is set. So far, peaks in the acceleration signal for a plate have been selected by eliminating the largest peak in the data set, averaging the amplitude of the next 10, and then requiring a peak prominence that is 40% of that magnitude. This level was selected because it provided the highest rate of correct detection, but it is not ideal for every sample. Figure 4.19 shows one sample where the selected threshold was too low; in addition to finding the high amplitude peaks, it identified a number of peaks with lower amplitude, often right next to the large ones. This causes the peak frequency calculation to judge the plate as smoother than it really is. Note that this figure only shows the vibration caused by one of the grooved plates, because the threshold for the other plate in this sample was set independently.

The 40% figure was selected out of a range of values, because it correctly identified the most samples correctly: 1072 out of the 1338 total. When a threshold lower than 40% is used, smaller, non-important peaks get counted more often (as shown in Figure 4.19), so that the algorithm is no longer just counting peaks that are caused by the cane tip interacting with a groove, and the correct prediction rate decreases. As the threshold is increased, the total number correct begins to decrease as well: at 50% the algorithm correctly detects 1061 samples, at 60% it correctly detects 1032 samples, and by 66% (the largest fraction considered) it correctly identifies 1010 samples. As the threshold is increased, it becomes more likely that the algorithm will skip peaks that are significant but have somewhat smaller amplitude, and will interpret the plates as rougher than they really are.

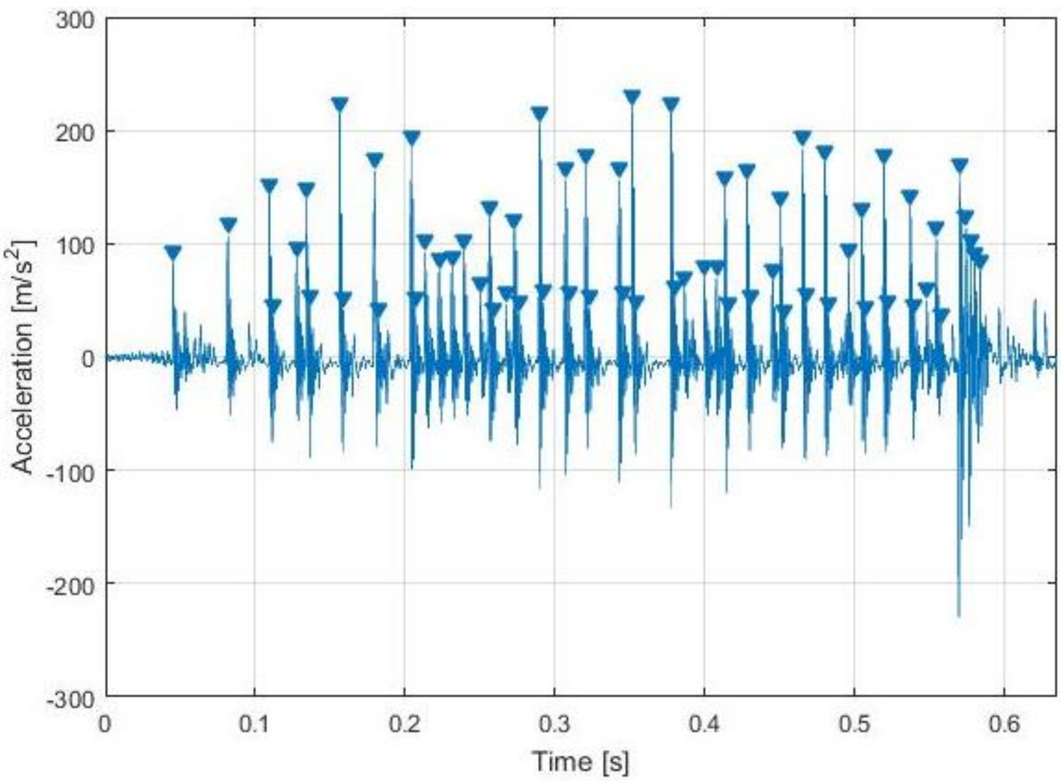

Figure 4.19: Peak selection for one plate, where the minimum prominence threshold is too low.

One other threshold also predicted the plate roughness equally well. At 46%, 1072 samples were also correctly identified. This level resolved several samples where the threshold was too low and too many peaks were counted, but also missed several samples where important peaks had amplitudes too small to be considered. Table 4.7 shows the detection rate at 40% and 46% thresholds, by block condition. Interestingly, the higher threshold did slightly better in the rigid high speed and flexible low speed conditions, and worse in the rigid low speed and flexible high speed conditions. There is no clear reason why this is the case; with as small as the difference is between the two thresholds, it may be coincidental.

Table 4.7: Number of correct detections using 40% and 46% threshold.

Block Condition	Number of Samples	Number correct – 40% threshold	Number correct – 46% threshold
Rigid Low Speed	341	281	276
Rigid High Speed	322	240	244
Flexible Low Speed	343	291	295
Flexible High Speed	332	260	257
All Conditions	1338	1072	1072

There are also some samples where one threshold level is not a good fit to the whole plate scrape, because the amplitude changes significantly across the plate. Figure 4.20 shows three examples. Again, each plot is only for a single plate (half of a scrape), because the threshold for each half is set independently. In each case, the threshold seems to be a good fit for a portion of the sample, but there is a section with less intense vibration, such that no peaks are detected for a large time interval. When the peak rate is calculated, it counts the number of important peaks, and then divides by the time interval between the first and last peaks. If there is a large section without evenly spaced peaks, the peak rate will be lower than it should be, so the script interprets the plate as rougher than it otherwise would.

There are several possible solutions to this issue. The most straightforward is to manually trim each sample that shows this trend, and only consider a fraction of the accelerometer output which is more uniform in magnitude. However, this can quickly become labor-intensive: One must identify all of the peaks, plot each sample, manually inspect each one, and trim down any sample where an issue is found. Another possible option which has not been investigated here is to set the peak threshold by fitting an envelope to the scrape signal, and using a fraction of the moving envelope rather than a fraction of some static amplitude value. This method was considered early on in this work, but not used because of the relative difficulty of implementing it in MATLAB. It is also possible that a script could be written to identify large sections of the time signal without any peaks, and automatically truncate that section from the sample.

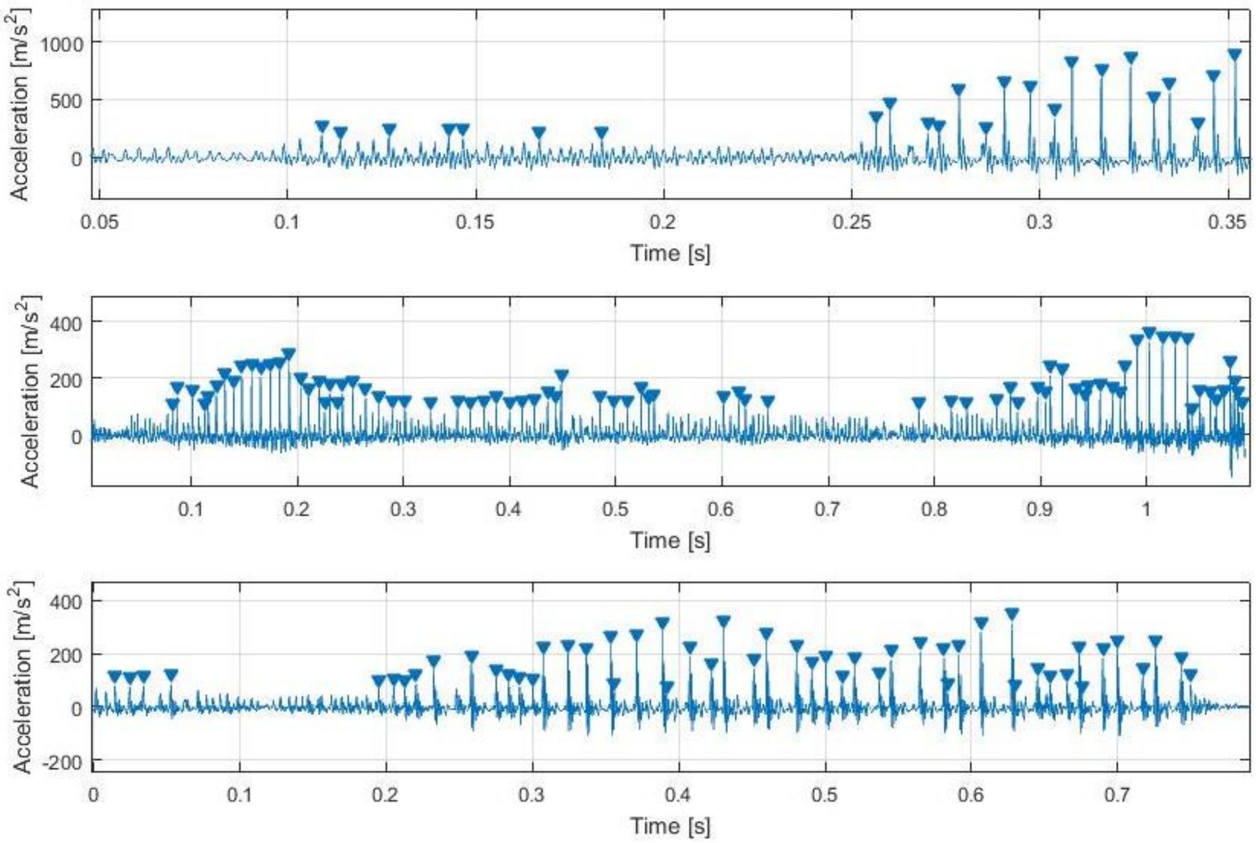

Figure 4.20: Three examples where a constant threshold is not a good fit to the scrape sample.

Finally, it was discussed earlier that some samples were eliminated because the majority of one plate was not present in the accelerometer output, but samples were retained when it seemed that there was a large enough fraction of each plate to be representative of the cane vibration. It is possible that some of these really do not represent what the participant felt across the whole plate, and they should have been eliminated but were not. It is difficult to know for sure whether a section of data is representative, and while the author believes that each of the included samples was, that may not truly be the case.

4.9. Other Analysis Methods

Two methods were developed to process the vibration response of the cane while the user scrapes the two grooved plates, in order to determine which plate is rougher. In the first method, high amplitude peaks are identified that are likely caused by the cane tip falling into consecutive grooves in the plates, and the rate of these peaks is compared from one plate to the other. In the second method, the relative amplitude of these peaks is considered, where higher amplitude peaks indicate the rougher plate. Several other methods were investigated, and while they did not turn out to be effective, it is worth briefly noting them.

Both of the methods used here process the cane vibration response in the time domain. That is, they look for events that happened in the time record of the accelerometer output and quantify how the signal changes as time goes on. It is common in vibration analysis, however, to consider phenomena in the frequency domain. In the frequency domain, events are selected and the relative distribution of energy across the frequency spectrum is considered. It seems reasonable that the spectral content of the cane vibration may change with surface roughness, so frequency content should be considered. In fact, the peak frequency method that was used is an estimation of a change in the frequency domain, in that it considers the frequency change from one plate to the other, for one component of the cane vibration (the large peaks).

Figure 4.21 compares the power spectral density (PSD) of the left and right plates for one sample (number 27 from Table 3.3, time record shown in Figure 4.1). The horizontal axis now shows the frequency of interest, and the vertical axis shows the relative intensity of the vibration. The two plots show PSD for each plate separately. When looking for the frequency response associated with the large peaks, we should see some feature in the PSD that is at a higher frequency for the smooth plate than for the rough one, because the energy associated with the large peaks happens more often in the smooth plate than the rough one.

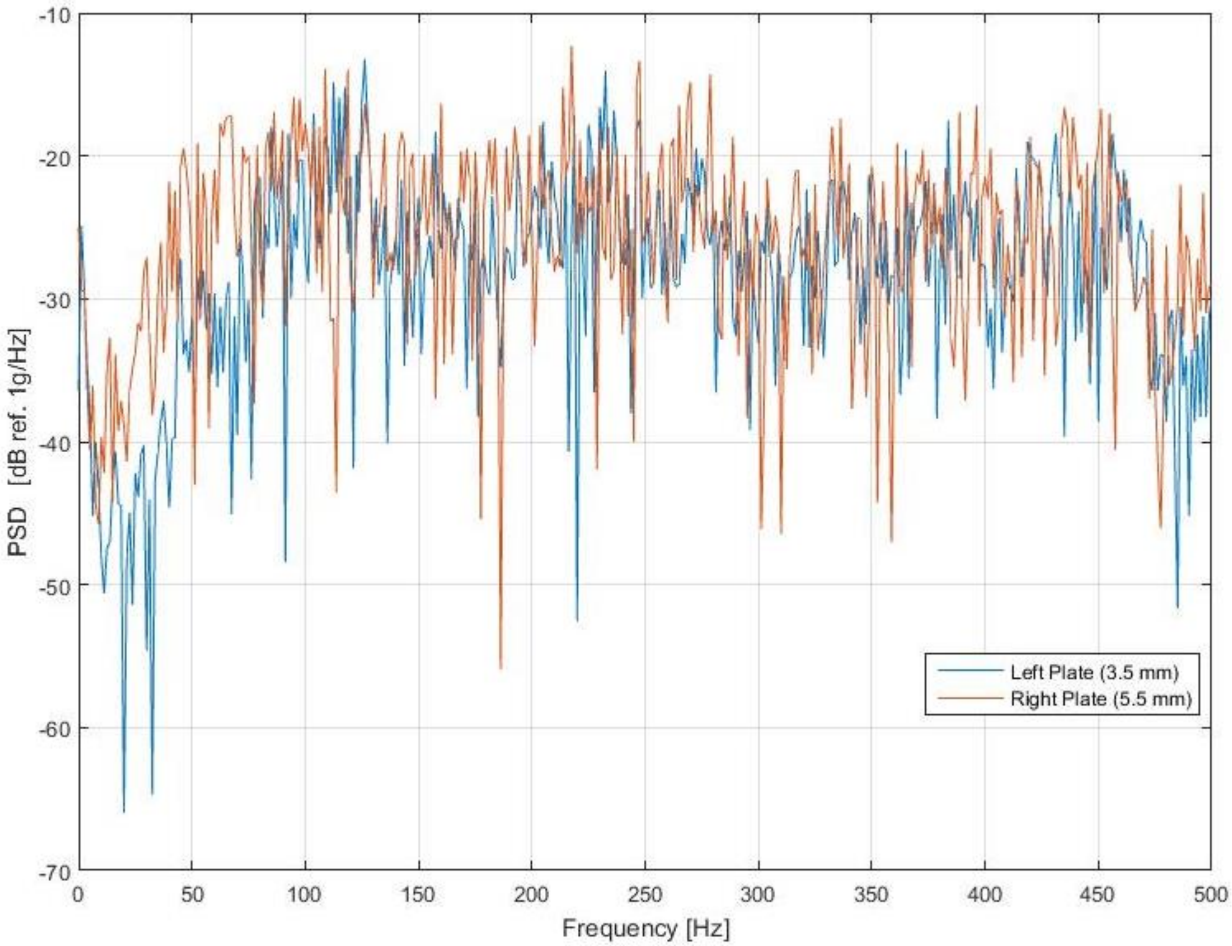

Figure 4.21: Sample power spectral density for one pair of plates.

Looking at the figure, there is a difference in the two plots below 100 Hz. It does seem like the upward trend for the 3.5 mm plate is shifted right, when compared to the 5.5 mm plate, but it is not clear what is causing this difference. It could be caused by the change in peak rate, but it is also expected that a rougher surface produces higher overall amplitude vibration, and so that amplitude increase could just be focused in the frequency range below 100 Hz. There is also the yet-unknown effect that causes the right plate to show higher amplitude vibration than the left plate, regardless of the change in texture. All three of these effects are indistinguishable in the figure. There is also no way to compensate for changing downward cane tip force on the grooved plates, which will changes the overall intensity of vibration and may shift the whole PSD plot vertically. Even with these issues aside, it was difficult to find a method to convert these qualitative observations about the vibration spectrum into a quantitative measure that could be used to predict the relative plate roughness.

Another way to visualize the change in spectral content with time is by using a spectrogram. Figure 4.22 shows a spectrogram of the same sample, with the original time signal also provided here for reference. The horizontal axis shows time, the vertical axis shows frequency, and spectral intensity is shown with color, from deep blue for low intensity to bright yellow for high intensity. The advantage of this visualization is that prominent changes in the vibration across time are easily noted. In fact, the interface between the two plates is clearly visible in this example at 0.75 seconds. The peak caused by the cane going over the interface is visible as a bright stripe, with the low amplitude section that is dark in color on either side. Although helpful for visualizing changes in the spectrum of a signal over time, it did not turn out to be quantitatively useful in this work.

The Frequency Response Function (FRF) was also examined to look for differences related to the change in groove size, or the difference between canes or swing speeds. An FRF is a measure of how the vibration of a structure changes between two points. The structure is excited at one point and its response is measured at a second point, and the change in intensity of vibration at certain frequencies gives information about the vibration of the structure. In this case, the signal from the cane tip accelerometer is used as the excitation measurement and the signal from the handle accelerometer is used as the response. Figure 4.23 shows the frequency response of the rigid cane in four randomly selected trials, with two trials at low speed and two at high speed. Figure 4.24 shows the frequency response of the flexible cane in four randomly selected trials. Again, two are at low speed and two are at high speed.

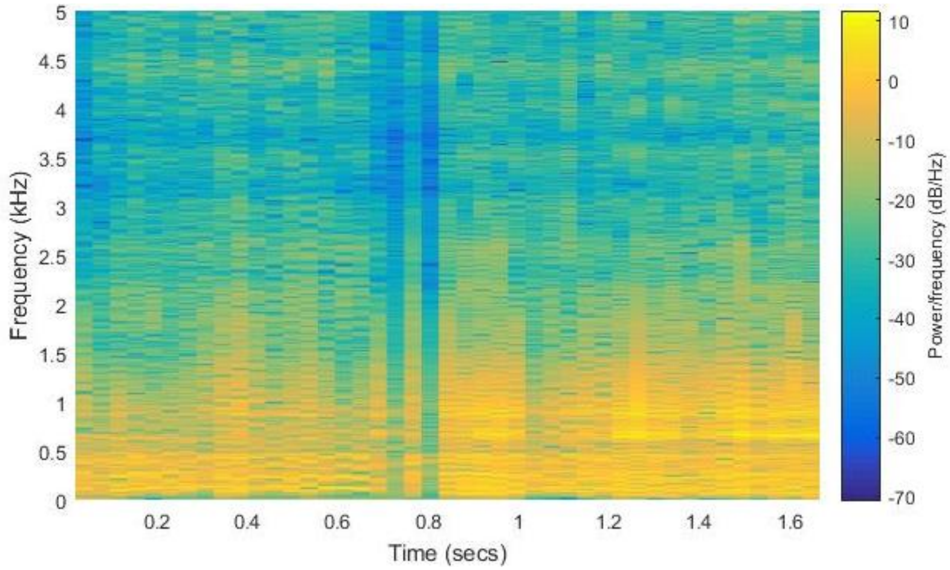

Figure 4.22: Time-Frequency spectrogram of one sample.

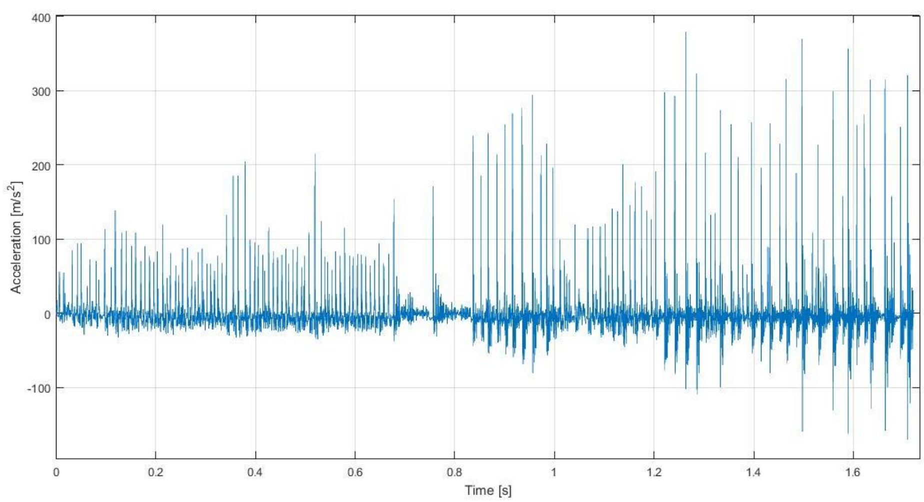

Figure 4.1: Tip accelerometer response for Sample 27 in rigid low speed condition.

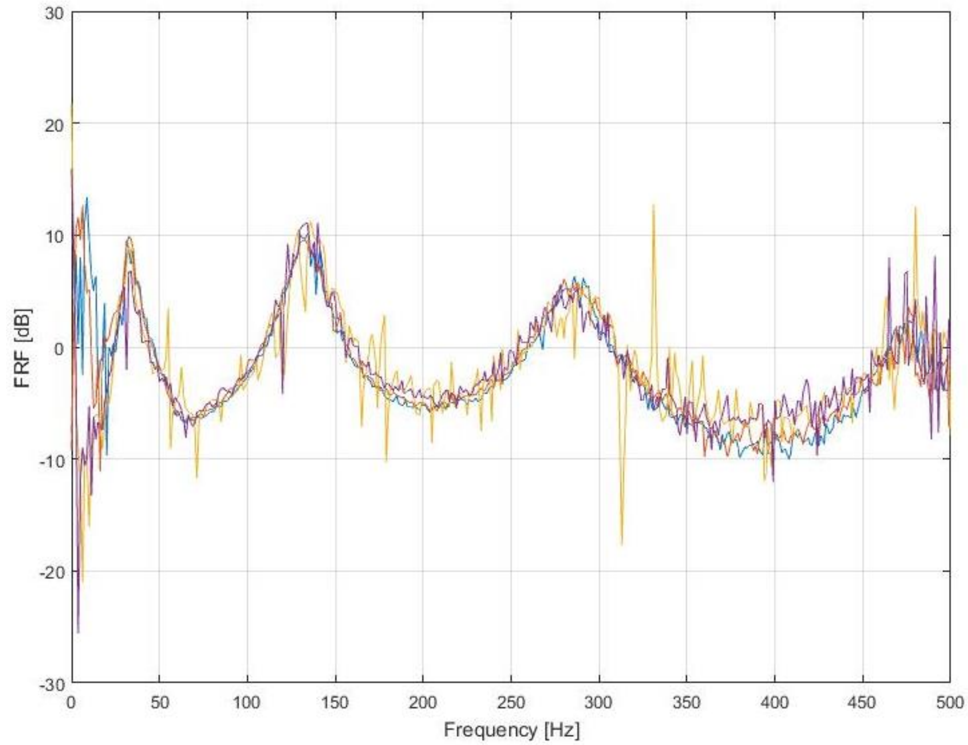

Figure 4.23: Rigid cane FRF for four randomly selected samples.

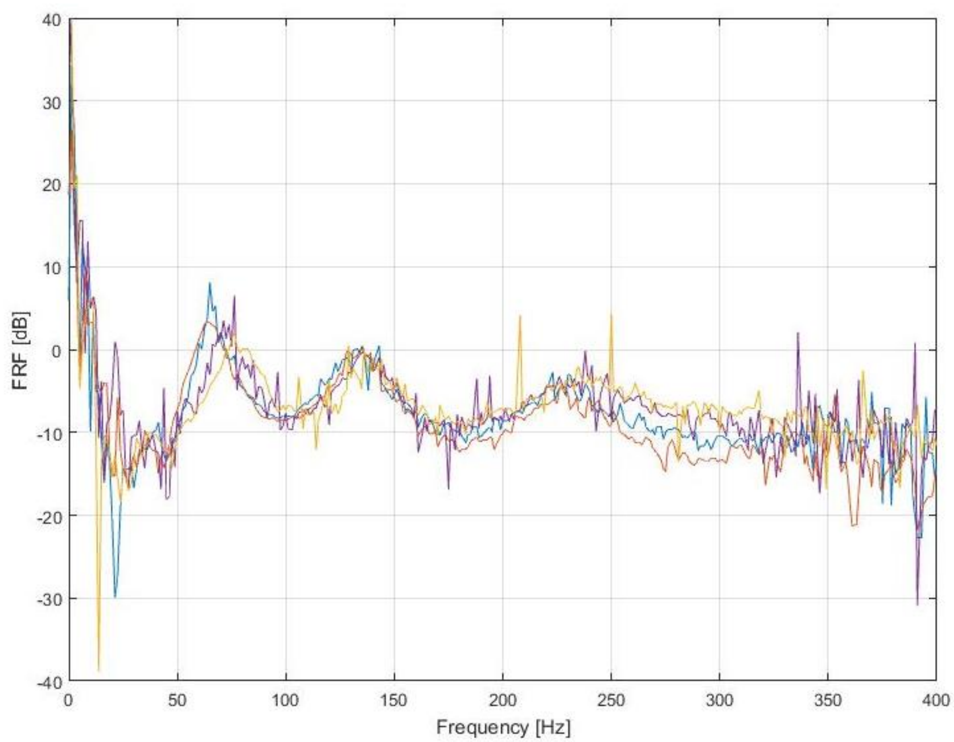

Figure 4.24: Flexible cane FRF for four randomly selected samples.

Vibration at frequencies where the FRF is positive is amplified from the cane tip to the handle, and vibration at frequencies where the FRF is negative is attenuated. Peaks in the plot indicate resonances of the cane. In each of the figures, the FRF plots from each of the four samples line up on top of each other. This is the expected result, because the frequency response should depend only on the properties of the cane shafts, and not on the nature of the excitation at the tip. In principle the FRF could be used to distinguish between different canes using the vibration response, but it is not useful for identifying the rougher of a pair of plates.

Another consideration when measuring the peak frequency difference between two plates in the time domain was to filter the accelerometer response to remove high frequencies. Refer again to Figure 4.1. Adding a low pass filter before processing the data may be helpful in removing the lower amplitude peaks that are not of interest, so that the algorithm is more robust to changes in the peak amplitude. It may also be useful to filter out high frequencies because of the insensitivity of the human hand above 500 Hz. By removing higher frequencies from the time signal, it may be more representative of the perception of the cane user. Low pass filters were added to the MATLAB script with cutoff frequencies ranging from 100 Hz to 1 kHz.

When the cutoff frequency is set too low, so that it approaches the frequency that the high amplitude peaks happen in the time signal, it will attenuate the high amplitude peaks that are caused by the cane tip interacting with the plate grooves. This was common with the 100 Hz filter and the high speed cane condition. Even if the cutoff frequency is set higher than the frequency of the large peaks, the filter may reduce the amplitude of these peaks. This is because the peaks are very sharp and brief, rather than sinusoidal in shape. This means that there must be higher frequency components involved in shaping the peaks, and by filtering out the high frequency content, the peaks become more "rounded" and less clear. As the cutoff frequency approached 1 kHz, the detection rate tended toward the unfiltered level.

Using a filter with a 300 Hz cutoff frequency, the peak frequency method correctly identified 1089 samples, compared with 1072 samples when unfiltered. Table 4.8 shows the difference in detection rate by block condition. It is interesting to note that adding the filter increased accuracy for the rigid cane, but not the flexible one. Even then, it was more pronounced at the low speed condition. It is not clear why this is the case; it may be because the stiff cane has higher natural frequencies, so proportionally more vibration energy was filtered out for the stiff cane compared to the flexible one, and the filter does a better job "cleaning" the signal without removing the important peaks. Cane natural frequencies were determined in an earlier study [11]. Figure 4.25(a) shows the unfiltered response from one sample in the rigid low speed condition, while Figure 4.25(b) shows the same response after applying the 300 Hz low pass filter. The filter reduces some of the cane resonance, but also reduces the amplitude of the large peaks.

Table 4.8: Detection rate by block condition, with low pass filter using 300 Hz cutoff frequency.

Block Condition	Number of Samples	Number correctly identified - Unfiltered	Number correctly identified – 300 Hz cutoff frequency
Rigid Low Speed	341	281	295
Rigid High Speed	322	240	245
Flexible Low Speed	343	291	290
Flexible High Speed	332	260	259
All Conditions	1338	1072	1089

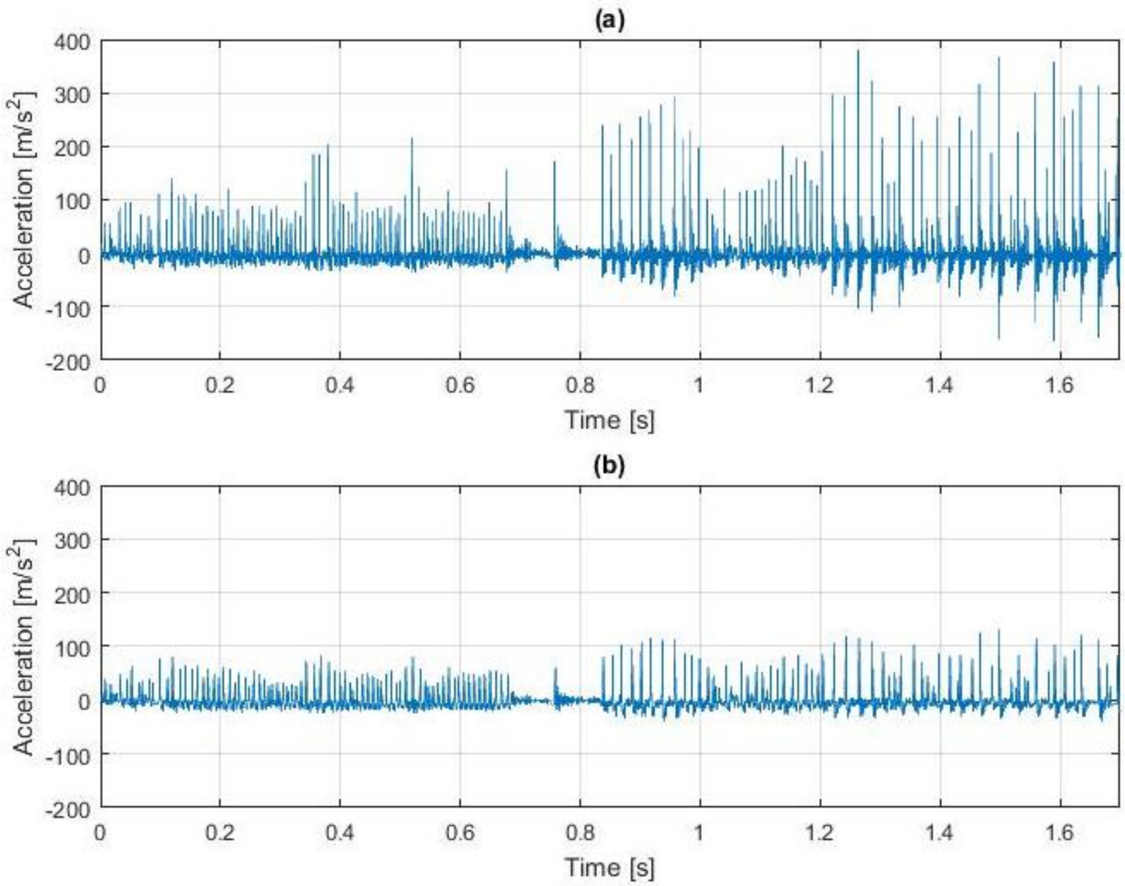

Figure 4.25: (a) Unfiltered signal from one sample in rigid low speed condition, and (b) signal with 300 Hz low pass filter applied.

4.10. Application to Secondary Set of Data

Finally, the peak frequency and peak amplitude algorithms were applied to a second set of samples to get a sense for the algorithms' robustness to changes in the experiment conditions. Sixty samples came from a small (3 participant) pilot study that was performed when designing the texture discrimination experiment outlined in this work, and there were several significant differences between the two studies. The pilot study used only one cane, which was made from graphite and 52 inches in length. Five cane tips were used: a pencil tip, marshmallow tip, roller marshmallow tip, ball tip, and roller ball tip. The sampling rate and other data collection parameters were identical to those used in the larger study. The plates used were rougher; a plate with 7 mm grooves was used as the reference, and plates with grooves ranging from 4 mm to 10 mm in 1 mm increments were compared to it. The general procedure was the same, in that the participant scraped once from left to right then had to select the rougher plate. However, the scrape speed was not controlled, so the participant could scrape at any speed that was comfortable. It was noted that one participant seemed to scrape much slower than the other two.

The 60 trials processed all used the ball tip. This is to maintain continuity, because the MATLAB script was developed using two canes with ball tips. The ball tip was also the largest in diameter, and so was the least likely to get stuck in the larger plate grooves. Some of the smaller tips, like the pencil or marshmallow tip, would frequently get caught in the grooves on the right side so that there was not a smooth, even scrape across the whole surface. Of the 60 samples, six were eliminated because of a poor recording, and 11 were eliminated because the interface of the two plates could not be identified. It was more difficult to identify the plate interface in the pilot study because the plates were set together such that the smooth area of one plate was facing in toward the center, but the smooth area of other was at the far edge, and so the low amplitude area between the two plates is shorter. Table 4.9 shows the correct detection performance by algorithm, and by participant.

Table 4.9: Correct detection rate in pilot study.

Participant	Number of Samples	Number correctly identified - Participants	Number correctly identified – Peak Frequency	Number correctly identified – Peak Amplitude
1	25	25	20	16
2	11	9	8	5
3	7	5	5	6
All	43	39	33	27

The participants correctly identified the rougher plate 90.6% of the time compared to 80.6% in the larger study. The peak frequency method was correct 76.7% of the time, compared to 80.1% in the larger study, and the peak amplitude method was correct 62.8% of the time, compared to 79.0% in the larger study. The participants most likely performed better in this pilot study because speed was not controlled, and because the textures were more coarsely graded (1 mm increments, rather than 0.5 mm increments). The participant that was noted to swipe very slowly was correct in every choice he made with the ball tip. The detection rate with the peak frequency method seems to be comparable between the two studies.

The peak amplitude method did not perform well with the pilot study data. In the larger study, the vibration amplitude method did better with the rigid cane than the flexible one, so it may be that the method is simply less effective for the graphite cane used here. It is also important to note that the cane used here has an elastic band that runs inside the cane down its length. This is common for folding canes to hold the segments together, and it was used in the pilot study to hold the cane tip on by pulling it up from the inside. The elastic band changes the stiffness and damping of the cane; it may also bounce around inside the cane while in motion and provides a second path for vibration to the handle from the cane tip. These changes in the cane vibration characteristics may be have obscured the roughness effect on the amplitude.

4.11. Concluding Remarks

Two methods were developed to post process the vibration response of the cane when scraped across two textured surfaces, in order to determine which of the two was rougher. In the first method, a MATLAB script identifies high amplitude peaks in the data that seem to be caused by the cane tip impacting grooves in the plates, and the difference in frequency of these peaks between the two plates is used to determine the rougher surface. In the second method, the relative amplitude of these peaks is observed between the two plates, and the one that produces the higher amplitude vibration is selected as the rougher plate. Both of these methods correctly identify the rougher plate as well as the cane users do. Both methods also perform better in the low speed condition but equally well for both canes, as do the participants. This seems to indicate that both the frequency of high amplitude peaks and the relative amplitude of the two sides are important cues used by the participants in identifying the rougher plate.

CHAPTER 5

DROP-OFF DETECTION PILOT STUDY

This chapter describes a pilot study that was performed to investigate the use of cane vibration characteristics during another part of the surface preview walking task: drop-off detection. An introduction to drop-off detection as a navigation task is given in Section 5.1, followed by the experimental design used to quantify it in Section 5.2. The instrumentation used in this study is described in Section 5.3, and then the results from the first data collection session are discussed in Section 5.4. Section 5.5 describes a method that was used to synchronize the vibration measurement with an optical position tracking system, and results from a second data collection session are shown in Section 5.6. Section 5.7 summarizes the pilot study.

5.1. Drop-Off Detection Task

Drop-off detection refers to the ability of a blind pedestrian to notice a step down in the walking path, as when walking toward a flight of stairs or off of a curb. It is important for the safety of a cane user that he or she is able to detect a drop-off, because missing a vertical change in the walking surface can cause stumbling or falls, resulting in injury or worse, stumbling into the path of oncoming vehicles.

A cane user is alerted to the presence of a drop-off in the walking path through two mechanisms: the vibratory response of the cane as the tip slides over the edge of the drop and lands on the lower surface, and proprioceptive feedback in the wrist and elbow [11].

Proprioception is the awareness of the present position of the body; a white cane user will notice the change in wrist and forearm position as the cane tip slides off the edge of a drop-off. There has been limited research in how these two mechanisms help a blind pedestrian detect a drop-off, but no study has directly measured the vibration of the cane while it is in use in order to identify the vibratory cues involved in the task.

5.2. Drop-off Detection Experiment Design

To measure drop-off detection performance, previous studies [2], [8], [10], [11] have had participants walk down a raised walkway while scanning the path with a cane. A second, lower platform was set at the end of the walkway, and its height was varied in order to change the size of the drop-off from the first surface to the second. The participant was instructed to stop and verbally identify the drop-off if they noticed it in the path. In cases where the participant did not notice the drop-off when the cane went over the edge, an Orientation and Mobility (O&M) specialist intervened so that they did not stumble over the edge. In some studies, optical markers were placed on the participant and the cane, to collect motion information during the approach to the drop-off.

5.3. Instrumented Cane Hardware

To understand how vibratory cues are interpreted by a cane user to detect a drop-off, the vibration of the cane must be measured at the moment it goes over the drop-off, along with whether the cane user noticed the presence of the drop-off. We can learn about how the user interprets vibration in the cane handle by examining the difference in cane vibration between samples where the drop-off was detected and those that were not. This entails mounting accelerometers on the cane and recording the response with some kind of data acquisition system. When instrumentation is added to a cane used for a drop-off detection task, it is important that the setup does not interfere with the natural motion of the cane user, because in this experimental design, the participant is no longer stationary but walks down a runway.

There are three possible ways to collect the vibration response while allowing the participant to freely move around. First, the participant could be connected by a long tether wire to a stationary workstation running data collection software. This solution does not require any additional hardware, but the participant must be careful not to trip on or snag the wire, and may find the tether restrictive or distracting. Second, the accelerometers could be connected to a wireless transmitter that broadcasts the data over a local wireless network to the stationary workstation. Third, the participant could carry the whole system with them, including a laptop running data recording software. This solution requires the user to carry significantly more equipment, and it may be difficult to operate the software. For this study, a wireless transmitter chassis was selected.

Two accelerometers were mounted to a cane to measure its vibration, as was done for the texture discrimination experiment. Again, one was mounted just above the cane tip, and one just below the cane handle. The wired NI-USB-9162 chassis that was used for the texture discrimination experiment in Chapter III was replaced with a National Instruments cDAQ-9191 Wi-Fi chassis and lithium ion battery pack that are carried by the cane user. This chassis wirelessly connects the NI-9234 analog data acquisition module to a computer running Smart Office Analyzer, over a local Wi-Fi network. Figure 5.1 shows the chassis and battery pack.

In addition to the two accelerometers, a dynamic force gauge (PCB Piezotronics 208C02, usually mounted on impact hammers used in modal testing) was mounted to the cane tip in order to measure the impact force between the cane and the walking surface. The force gauge measures in only one direction, so it must be mounted at an angle such that it is held normal to the walking surface. Several standard pencil tips were modified to remove a flat section at an angle, and a threaded hole was added to mount the force gauge. The angle of each flat section was different so that one could be selected that holds the force gauge normal to the ground, depending on the cane length and user's height. Figure 5.2 shows the four modified pencil tips. The angle noted on each refers to the angle of elevation of the cane for which each tip should be used.

By adding a force gauge to the cane, in addition to measuring the vibration response of the cane while in use, the excitation force from the ground (or the drop-off) could be directly measured. The tip attached to the force gauge was fabricated from aluminum and was hemispherical in shape, and was used because it helped prevent snags and hang-ups when compared to other tips typically used with an impact hammer. Figure 5.3 shows the force gauge mounted on the tip of a white cane. Figure 5.4 shows the hemispherical tip on the far left, along with several manufacturer-supplied tips for the impact hammer.

Figure 5.1: NI cDAQ-9191 Wi-Fi chassis and lithium ion battery pack.

Figure 5.2: Modified cane pencil tips, used to mount force gauge to cane tip.

Figure 5.3: White cane with force gauge mounted to its tip.

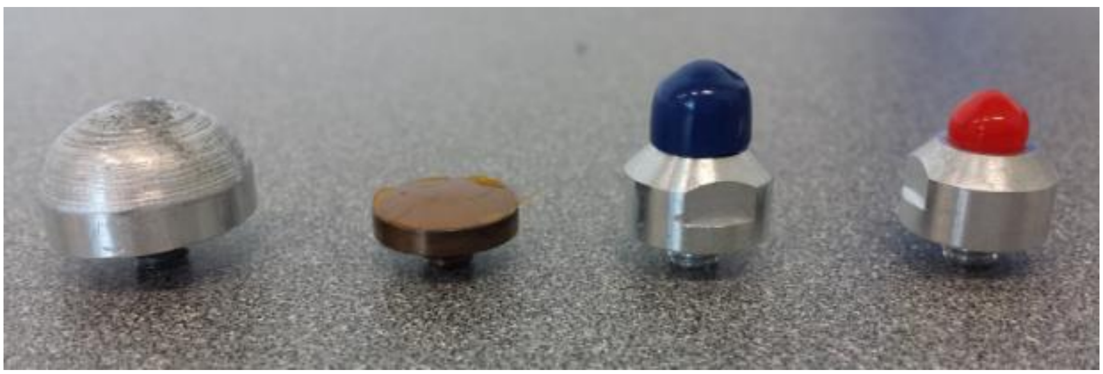

Figure 5.4: Fabricated force gauge tip, far left, along with several manufacturer-supplied tips.

In this drop-off detection study, a fishing vest was worn by the user to hold the transmitter and battery pack. A backpack or hip pack was also considered. However, the transmitter was too large to comfortably fit on the belt, and there were concerns that a backpack shoulder strap could interfere with the natural range of motion of the user’s arm, affecting his or her natural motion. The vest had a large pocket on the back that held the transmitter and battery, and the weight was spread evenly over a large area on the shoulders. The vest did not restrict arm motion, as it was designed to be worn while fishing, an activity that requires freedom of arm movement for casting. Figure 5.5 shows the vest, and Figure 5.6 shows all the components that the user carried during a trial: the cane, data acquisition module, Wi-Fi chassis, battery and vest.

Figure 5.5: Fishing vest worn during drop-off detection, to carry Wi-Fi chassis.

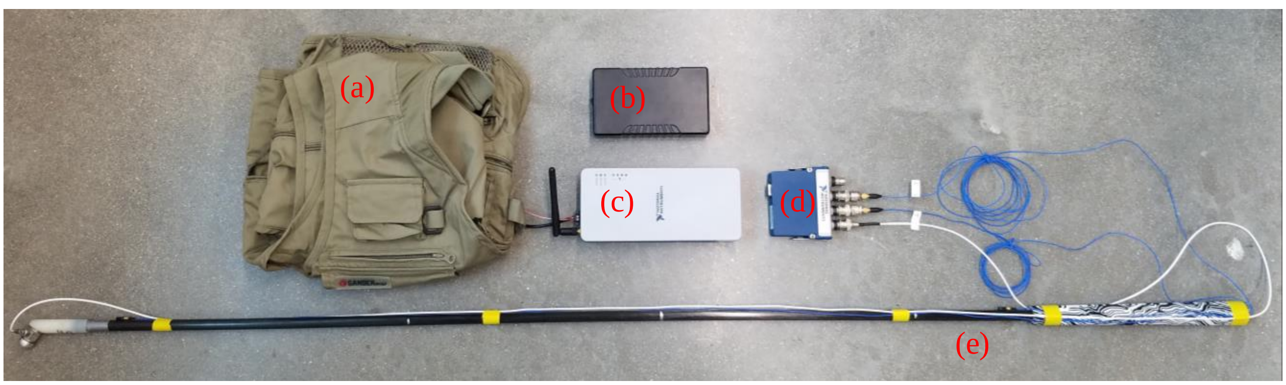

Figure 5.6: (a) Fishing vest, (b) battery pack, (c) Wi-Fi chassis, (d) data acquisition module, and (e) instrumented cane.

The position of the participant was also measured. The Optotrak Certus (Northern Digital) is a motion capture system that uses an array of three cameras to track the three dimensional position of markers through time. The markers are attached to a small battery pack carried by the participant, and each marker emits infrared light that is picked up by the cameras. A marker is placed anywhere on the participant where motion should be measured, in this case the cane tip, pointer finger, wrist, shoulders, torso and feet. The Optotrak recorded the position of every marker 100 times per second and reported X, Y and Z coordinates. In this experiment, the X direction is vertical, Y direction is lateral compared to the participant, and the Z direction is forward toward the drop-off. Coordinates are reported with precision on the order of millimeters, although the repeatability of these measurements has not been tested here.

5.4. Data Collection Session A

Two participants used instrumented canes in this drop-off detection study. The study considered two canes of different length and two swing arc widths. One participant used the constant-contact method, and the other used the two-point touch method. The short cane was made from poplar and was 46 inches in length, while the white cane was pultruded carbon and was 62 inches in length. The cane lengths are on the extreme short and long sides of what might be used by a blind pedestrian, and the materials were selected so that the two canes would have similar rigidity. In the narrow swing condition, participants swung the cane in an arc that extended out to the shoulder on each side. In the wide swing condition, the arc was several inches past the shoulder on each side.

The drop-off height was randomly set at 1, 3, 5 or 7 inches for each sample. Each participant performed four replications of every height, for each of the two canes and each of the two arc widths, so that there were 64 samples per participant. The vibration of the cane was recorded for each sample, and it was noted whether the participant identified the drop-off when the cane tip went over the edge. Motion of the cane tip, along with the participant’s index finger, wrist, shoulders and feet was recorded using the Optotrak Certus motion tracking system as the participant approached the drop-off.

After reaching the drop-off, the participant was asked to lift the cane up off of the ground and then deliberately tap it, in order to provide a reference for synchronizing the vibration and optical position measurements. Figure 5.7 shows a force measurement at the cane tip as the participant reaches the drop-off for one sample in the long narrow condition, using the constant-contact cane technique. The drop-off shown here is three inches tall. The participant scanned the walkway for the first seven seconds, and then the cane tip slid off the edge of the drop and hit the lower surface, creating the first large peak as indicated by an arrow. He then picked the cane up and deliberately tapped it, as shown by the very smooth signal from eight to 9.5 seconds, and the second large peak.

Figure 5.8 shows the motion of the cane tip during the same trial as recorded using the Optotrak. As stated previously, the X direction is the vertical elevation of the cane tip, the Y direction is laterally across the participant’s body, and the Z direction is forward toward the drop-off. The first thing that is noticed about the plot is that it is not continuous. The Optotrak will sometimes fail to locate all of the position markers, leaving a discontinuity where the position of the cane was not recorded. This will happen when the cane leaves the field of view of the motion capture cameras, or when the cane or participant is at an angle such that the markers do not face toward the cameras.

Remember that the time values in Figure 5.7 and Figure 5.8 cannot be directly compared, because the recordings were each taken independently, so we must find some common marker in both signals. Unfortunately, the cane tip was not visible to the Optotrak during much of the deliberate tap that was intended for synchronizing the position and vibration measurements. The X direction plot (which is the vertical elevation of the cane) shows the cane tip being lifted up in front of the participant and coming back down between seven and nine seconds, although the

Optotrak does not capture the top of the cane tip arc, or the bottom when the tip touches down again.

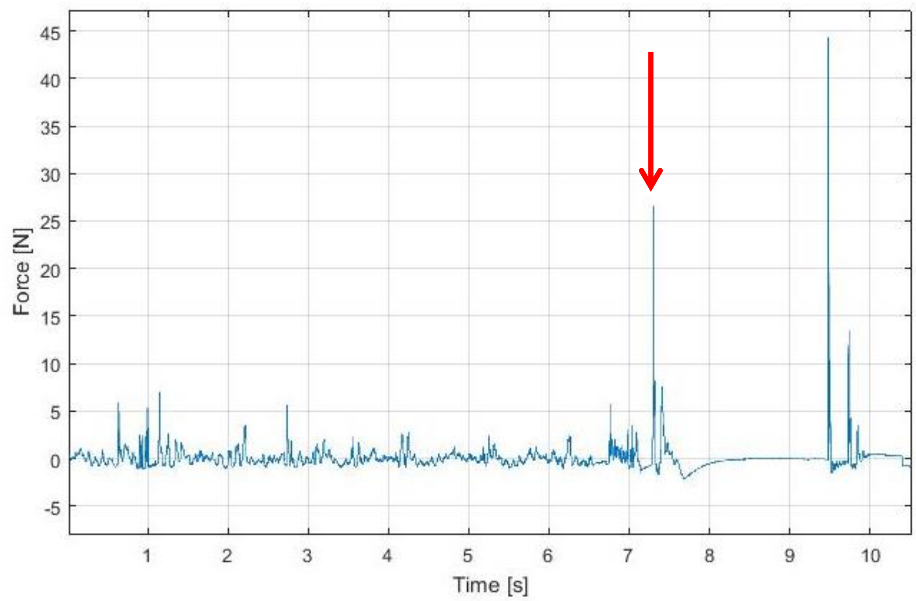

Figure 5.7: Time record of cane tip force for one constant-contact drop-off sample.

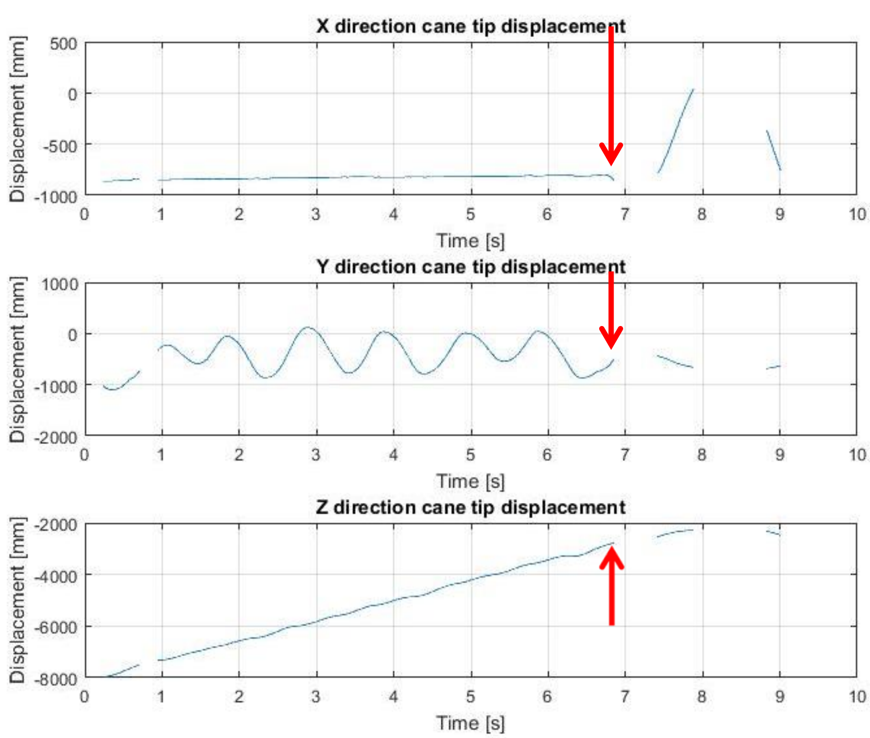

Figure 5.8: Time record of cane tip motion for one constant-contact drop-off sample.

It seems that the participant lifted the cane tip up such that the marker was pointing upward toward the ceiling and not forward at the cameras, then the cane either rotated in the user’s hand or dropped out of the bottom of the view area during the final tap. In this sample, however, the moment of the drop-off can be identified in the X direction measurement. The cane tip was at constant height as the participant scanned the walking surface with the constant-contact technique, then the cane tip suddenly decreased in elevation right before going out of sight of the cameras, just before the seven second mark. The drop-off location is indicated by an arrow.

Figure 5.9 shows the tip impact force time record of one sample in the rigid narrow swing condition for the second participant, who used the two-point touch technique. There are a series of regularly spaced peaks caused by the participant rhythmically tapping the cane down the walkway, and a large peak at the end of the sample from the deliberate cane tap used for synchronization. It is not clear which one of the peaks, if any, were caused by the cane falling across the drop-off. Figure 5.10 shows the position of the cane tip in the X (vertical), Y (lateral) and Z (forward) directions. The plot actually shows the position of two markers that were set on the cane tip side by side, so that the Optotrak would have a better chance of detecting at least one of them; this is visible on the X axis plot in some sections as two parallel lines.

Examining Figure 5.10, it is now difficult to identify the drop-off, or the deliberate cane tap. When using the two-point touch method, we are no longer able to identify the small decrease in elevation at the site of the drop-off, because the cane moves vertically with each step. The deliberate synchronization tap may have happened just after eight seconds, although part of the data record is missing. It looks like the participant stopped walking forward just before the six second mark, because the Z-direction plot stops increasing, but this does not help identify the point of the drop-off, or to synchronize the position tracking with the cane vibration measurement.

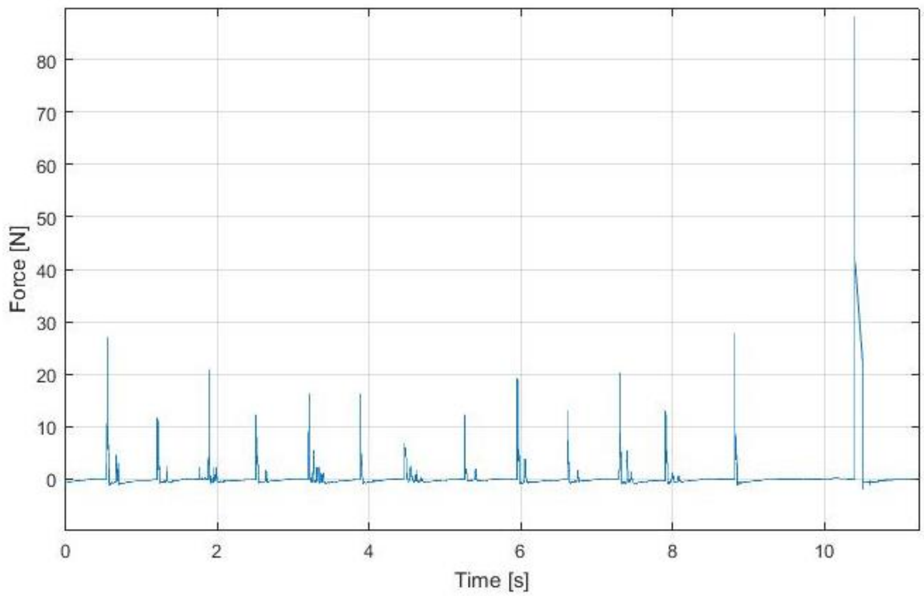

Figure 5.9: Time record of cane tip force for one two-point touch drop-off sample.

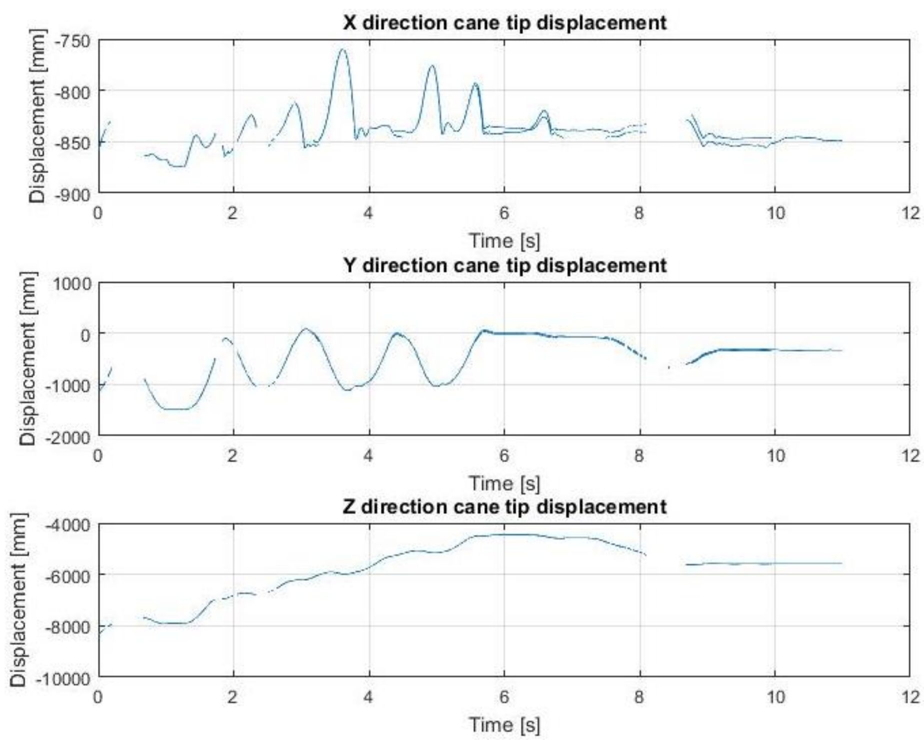

Figure 5.10: Time record of cane tip motion for one two-point touch drop-off sample.

The two samples outlined here are typical of the collected data from this session. It was difficult in many samples to identify the point where the cane tip crossed the drop-off, and in very few samples were the vibration and position measurements manually synchronized with any level of certainty.

5.5. Optotrak Synchronization

A deliberate cane tap was not effective for synchronizing the vibration measurement and optical position measurement during the drop-off detection experiment, because the Optotrak often loses track of the position markers. It is sometimes possible to identify the drop-off location in the vibration measurement, although this is difficult when the two-point touch method is used. In the ideal case, the drop-off could be identified in both the vibration and position measurements, so that we can simultaneously measure how the cane moved, how it vibrated, and whether the participant identified the drop-off. The Optotrak camera may be repositioned such that it better detects the cane tip at the drop-off, but even if every sample is completely recorded without any gaps, it will still require that the vibration and position recordings are manually aligned one sample at a time.

A better option would be to synchronize the Optotrak and vibration measurement at the hardware level, so that both systems can be triggered to start recording together and there is no uncertainty regarding the time difference between the two samples. There may still be some absolute time difference between the two, but it should not change between samples, so the two can be aligned automatically using a MATLAB script. The Optotrak supports using an external signal to start recording a sample, or it can be configured to send a trigger to another device when it begins recording a sample. Smart Office Analyzer can be set to begin recording a sample when it detects an external signal, but it cannot send a trigger to another device.

The two data recordings can be synchronized if a signal output from the Optotrak camera can be transferred to the National Instruments data acquisition module that is carried by the participant, but a physical wire connected between the camera and the participant should be avoided, because this will restrict the participant's movement. The trigger signal must be transferred wirelessly from the Optotrak to the data acquisition module on the participant. Two Arduino microcontrollers were used to implement a low cost radio transponder that reads the Optotrak output signal, and provides an input trigger signal to the National Instruments system.

An Arduino is an open source microcontroller that is popular for hobbyist electronics, and can be programmed to perform a range of simple tasks. Two boards (Arduino Pro 328 – 3.3V/8MHz) were each connected with a radio transceiver module (Sparkfun RFM69 – 915 MHz) and configured to communicate with each other. Figure 5.11 shows one of the microcontroller boards connected to a radio module. During data collection, one microcontroller is connected to the Optotrak output and watches for the output signal that indicates a recording session has started. When the trial starts, it sends a radio signal to the other microcontroller, which is carried by the participant and feeds a trigger signal into the data acquisition module, triggering Smart Office to begin recording the cane vibration. Figure 5.12 shows a block diagram of the setup. The program running on each microcontroller is included in Appendix A. Using this arrangement, the time delay between the optical position measurement and vibration measurement is consistently 30 milliseconds. With the offset known, the two measurements can be easily aligned.

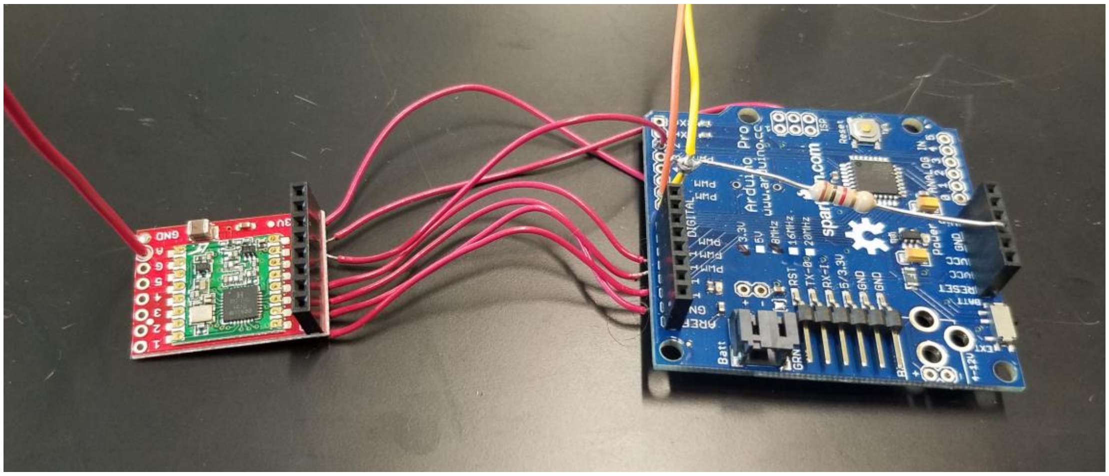

Figure 5.11: Arduino microcontroller, right, and RFM69 radio transceiver, left.

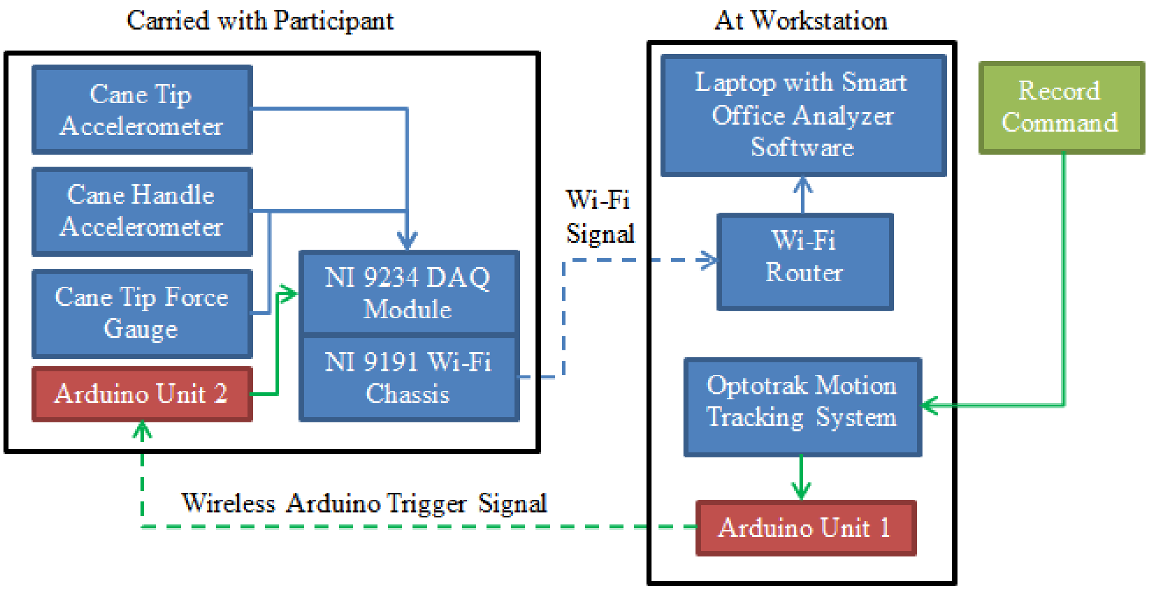

Figure 5.12: Block diagram of drop-off detection study setup.

5.6. Data Collection Session B

With a synchronization method developed, another data collection session was held to test it. One participant performed four replications each of four drop-off heights (1, 3, 5, and 7 inches), for both the constant-contact and two-point touch methods. Figure 5.13 shows the vibration of the cane and position of the cane tip for one sample, which had a three inch drop-off and used the constant-contact technique. Note that this time, the time dimension is synchronized between all measurements. The drop-off occurred just after six seconds.

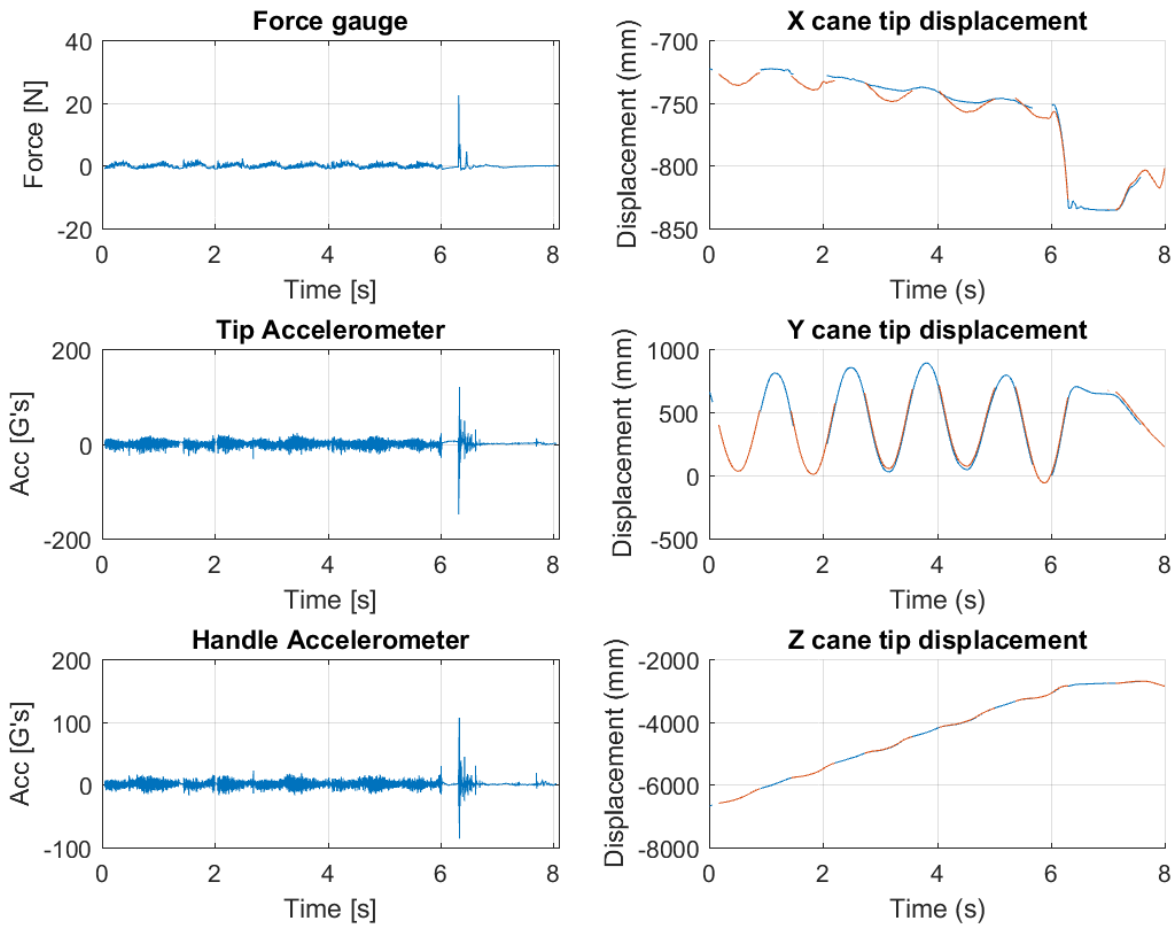

Figure 5.13: Synchronized cane tip position and cane vibration response, with constant-contact technique.

Figure 5.14 shows a sample that used the two-point touch technique. It is clear from the X direction cane tip displacement that the cane tip went over the drop-off just after six seconds. We no longer need an obvious marker in both sets of data to synchronize the data because they are started at the same time; rather, we can observe both the cane motion and cane vibration and compare both of these to the participant performance.

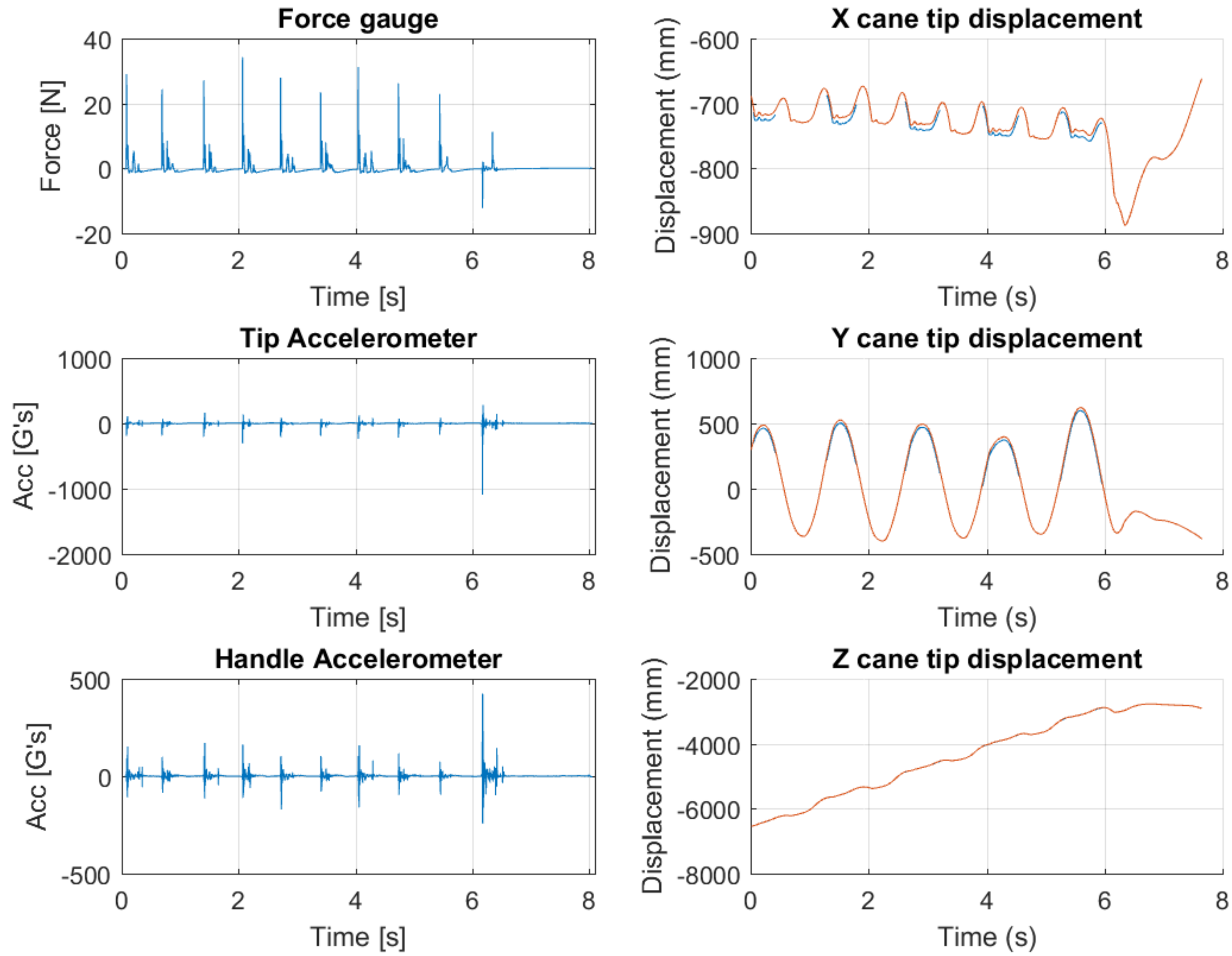

Figure 5.14: Synchronized cane tip position and cane vibration response, with two-point touch technique.

In the first session, the raised walkway leading to the drop-off was covered with a carpet runner down its whole length. However, the runner was not as wide as the walkway, so the cane tip would sometimes get caught on the carpet edge. In some cases it was not clear if a peak in the force measured at the cane tip was caused by the drop-off or because the tip was dragged over the edge of the carpet runner, so the carpet was replaced with a single sheet of smooth vinyl flooring which covered the whole width of the walkway. The idea was to reduce the amount of vibration caused by the cane interacting with the walking surface, so that the drop-off would be more noticeable in the vibration measurement.

The vinyl covering did make it easier to identify the drop-off from the tip force gauge, but it also made it much easier for the participant to notice the drop-off, to the degree that the heights selected for the drop-off are no longer small enough to measure a detection threshold. The participant missed four trials out of 40, and all four were at the smallest drop-off size of one inch. The carpet was making the detection task more difficult, so that the larger sizes were sufficient, and the carpet runner should be used in future experiments.

While this makes it difficult to draw conclusions about how vibration is important for drop-off detection, the location of the drop-off was identified in the vibration and position measurements with certainty in 32 of the 40 samples. In some of the other samples, it seems that the participant did not make it to the drop-off by the end of the recording, and this can be fixed in future sessions by increasing the recording time or manually triggering the recordings when the participant is closer to the drop. In some of the other samples where the drop-off was not identified, the Optotrak lost sight of the cane tip, and this can be prevented by changing the camera positions so that the drop-off is better detected.

5.7. Summary

This pilot study developed a method to wirelessly measure the vibration of a white cane while it is in use by a pedestrian navigating through a space. In a drop-off detection study, the cane vibration can be measured and synchronized with cane position information gathered using an Optotrak Certus optical tracker, in order to identify the moment when the cane crosses over the drop-off. These measurements can be compared to participant performance to learn about how vibration cues are used to detect a drop-off. Although this work did not continue beyond what is outlined here, this pilot study lays the groundwork for future investigation.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1. Conclusions

The white cane is the primary mobility aid used by many people with vision impairment, but its design has not changed substantially since its development in the 1940s. A blind pedestrian swings the cane in front of him or her to check for obstacles, to learn about the walking surface, and to preview the ground where they will place a foot during the next step. In this project, a study was performed to measure the effect of cane rigidity and swipe speed on the ability of a cane user to detect changes in the surface texture, and the vibration of the cane was analyzed. A pilot study was also performed to investigate the use of vibration cues for drop-off detection.

Participants were presented with two textured surfaces, allowed to swipe across the pair with a cane, and then asked to verbally identify which surface was rougher. Accelerometers mounted on the canes measured the vibration exhibited during each sample, and then two methods were developed to identify the rougher surface by analyzing the cane vibration. The first method finds the frequency of large amplitude peaks in the accelerometer output caused by the cane tip moving over grooves in the textured plate, and identifies the rougher plate as the one for which the peaks are spaced further apart in time. The second method looks at the relative amplitude of peaks between the two surfaces, and identifies the rougher plate as the one with higher amplitude.

Both analytical methods select the rougher surface correctly as often as the participants were able to. The participants and both analytical methods performed better in the low swing speed condition, but equally well with both canes. The fact that the performance of both analytical methods mirrored that of the participants indicates that the frequency of high amplitude peaks and the relative amplitude of the two plates may both be important cues for the participant when selecting the rougher plate. In samples where the frequency and amplitude were distinctly different, the participants and algorithms performed better, while in samples where both plates seemed similar or the vibration was obscured, the participants and algorithms performed more poorly.

A method was developed in the drop-off detection pilot study to wirelessly measure the cane vibration while it is in use for navigation. The data collection is synchronized with position measurements taken with an Optotrak Certus motion tracking system, so that the moment of the drop-off can be identified in the cane vibration measurement. This study lays the groundwork for future investigation.

6.2. Future Work

There are many potential areas of improvement and expansion related to this project, beginning with the peak frequency and amplitude measurement algorithms. Chapter IV discussed limitations associated with the way a threshold is selected to identify vibration peaks. The method used here set a single static threshold for each plate scrape sample, which did not work well in samples where the amplitude of the peaks caused by the grooves in the plates varies significantly across the scrape, as may be the case when the participant does not swipe at a consistent speed or changes the downward force on the cane tip. It is possible that a better algorithm could be developed by fitting an envelope to the scrape sample, and identifying peaks that reach a certain fraction of the envelope size at the point of the peak. Another solution could look for sections in a sample where two consecutive peaks were unusually far apart, indicating that several important peaks may have fallen outside of the threshold, and then set a new threshold for that section or truncate the recording, so that the peak rate calculation is still representative.

The peak frequency method developed to identify the rougher of a pair of textured plates was based on the assumption that the participant took the same amount of time to scrape each plate in a sample. An average speed was calculated from the total swipe time, but there was no direct measure of the cane tip position in time during the cane swing. A future study should consider using the Optotrak position measurement system to record the movement of the cane tip in addition to recording the vibration of the cane. The two recordings can be synchronized as discussed in Chapter V. This will eliminate the need to make an assumption about the speed of the cane tip, as the speed can be directly measured. It also seems reasonable to directly measure the cane tip motion because the cane user likely has some sense of the cane speed across the swing. Imagine the case where the participant starts a cane swipe slowly, but speeds up as he or she goes over the interface between the two grooved plates. The peak frequency method will quantify the second plate as smoother than it really is, because the acceleration peaks are closer in time due to the faster cane speed. However, the participant may still identify the rougher plate correctly, because they have some proprioceptive sense of the cane speed across the swing.

As the peak amplitude method was developed, it was found that the plate on the right side of the swing often produced a higher magnitude vibration in the cane, regardless of the change in roughness between the two plates. The cause of this effect is unknown. It may be that the participants tend to swing the cane faster near the end of the swing, the participants apply more downward force on the cane tip on that side, or that it is a consequence of every participant being right handed. Further study is required to identify the cause and nature of this effect, and an analysis of the dynamics of the cane while in motion may be helpful. A future study should consider having participants swipe the cane in both direction, and tracking the cane tip motion to learn about changes in cane tip speed during the swing. Two identical surfaces could also be compared in some samples, so that any change in amplitude from one surface to the other is due to the cane swing, and not due to the surface roughness.

The peak frequency and peak amplitude methods developed here were applied only to the accelerometer mounted at the cane tip, near to where the cane interacts with the grooved surfaces; they were not as effective when considering the vibration at the cane handle, because the vibration has traveled up the length of the cane and the high amplitude peaks are not as easily discernable. However, the cane user is feeling vibration at the handle, which has been “colored” by the resonance of the cane. Algorithms should be developed that identify the rougher surface using vibration at the cane handle, as this is the vibration the participant is experiencing and using to make a selection. One possible method is to use the transfer function of the cane, which indicates how the vibration changes from the tip to the handle, to estimate the cane excitation at the tip from the response at the handle.

Single axis accelerometers were used in this study because they are lightweight and were readily available. They were placed on the top of the cane to measure acceleration in the vertical direction caused by interaction between the cane tip and the surface, but this ignores vibration in the transverse and axial directions. As a result, the acceleration measurements were sensitive to the roll angle of the cane in the user’s hand. Tri-axial accelerometers could be mounted to the cane to measure vibration in the other directions. It seems that one could calculate the sum of squares of the acceleration in all three directions to get a sense of the acceleration caused by the cane impacting grooves in the textured surface, in a way that is more robust to changes in the orientation with which the user holds the cane. Care should be taken when selecting sensors to avoid mass loading the cane and changing its natural vibration. Accelerometers should be selected that are as light as possible. Another possibility is to attach an inertial measurement unit to the cane to measure its angle of twist, as in [19], so that the angle between the cane excitation and accelerometer measurement is known.

The grooved aluminum plates in this study were used because they were a straightforward way to generate a set of textured surfaces with a quantifiable range of differences in roughness. Two plates with a 0.5 mm difference in groove dimension are more similar in roughness than plates with a 1.0 mm or 3.0 mm difference in groove dimension. However, it should be clear that these plates are not representative of the actual textures that a blind pedestrian will encounter while navigating through a space. A navigating pedestrian will need to be able to identify a change in surface from a concrete sidewalk to an asphalt parking lot, for example. Although the concrete sidewalk will not create the regularly spaced high amplitude vibration peaks that were used for analysis in this work, the frequency content change and amplitude change of the cane vibration are likely to be important cues in real-world texture discrimination tasks. Future studies should consider using surfaces that more closely mimic the textures that a blind pedestrian is likely to encounter.

This study considered the effect of cane swipe speed and cane shaft rigidity on texture discrimination performance. The cane tip and cane handle used were held constant, although they may also impact texture discrimination. The cane tip is the component that actually interacts with the walking surface, so changing the cane tip may change the characteristics of vibration excited in the cane. Likewise, the participant feels vibration transferred into the hand through the cane grip, which may filter vibration from the cane shaft. For example, a rubber grip might damp some of the vibration that is important for texture discrimination. Future study should consider the effect of different cane tips and cane grips on texture discrimination performance.

The texture discrimination study used 11 participants, 10 of whom had no vision impairment. Any inferences made from their performance may be valid for the larger population of graduate O&M students, but these inferences may not be valid for white cane users. Future study should include the participation of blind or vision impaired individuals when possible, especially when the results are to be generalized to the blind population.

Chapter V outlined a pilot study where the instrumented cane was used for a drop-off detection task, but no full scale study was performed. It seems likely that cane vibration is important for detecting a drop-off, especially when the constant-contact technique is used, because the cane tip is scrapped across the ground until it falls off the edge of the walkway and impacts the lower surface. The cane user may be noticing the tap of the cane on the lower surface to indicate a drop-off, and this could be investigated in further study. The cane tip interacts with the ground very briefly during each tap in the two-point touch technique, so that the cane vibration is caused by short, rhythmic excitations. It is possible that the amplitude of acceleration caused by the tap after the drop-off changes, but it seems likely that the cane user relies more on proprioceptive cues to detect the drop-off, when compared to the constant contact technique. If so, attaching instruments like a gyroscope to the cane might produce better insight. The instrumented cane provides an opportunity to learn about the relative importance of proprioceptive and vibratory feedback for the two cane techniques when detecting a drop-off.

6.3. Closing Remarks

This work identified the importance of two vibratory characteristics involved in the texture discrimination navigation task. These are the frequency of high amplitude peaks associated with large features in the surface and the change in vibration amplitude during the transition from one surface to another. This project is part of a larger effort to understand what factors influence navigation performance when using a cane. These factors include cane properties like length, weight, and stiffness, but also include other factors such as the scanning technique used (two-point touch or constant-contact) and the width of the cane swing in front of the body. A complete understanding of the factors that create an effective cane will allow the design of a cane that is optimized for the navigation tasks of the user, while understanding factors related to cane scanning technique will allow Orientation and Mobility specialists to better coach cane users in methods that enable them to navigate safely and easily. Continued work in this field will improve the safety and mobility of people who rely on the white cane for navigation.

REFERENCES

[1] M. D. Rodgers and R. Wall Emerson, “Human factor analysis of long cane design: Weight and length,” *J. Vis. Impair. Blind.*, vol. 99, no. 10, pp. 622–632, 2005.

[2] D. S. Kim, R. S. Wall Emerson, and A. B. Curtis, “Ergonomic factors related to drop-off detection with the long cane: effects of cane tips and techniques,” *Hum. Factors*, vol. 52, no. 3, pp. 456–465, 2010.

[3] B. B. Blasch, S. J. LaGrow, and W. De l’Aune, “Three aspects of coverage provided by the long cane: Object, surface, and foot-placement preview,” *J. Vis. Impair. Blind.*, vol. 90, no. 4, pp. 295–301, 1996.

[4] M. D. Rodgers and R. Wall Emerson, “Materials testing in long cane design: Sensitivity, flexibility, and transmission of vibration,” *J. Vis. Impair. Blind.*, vol. 99, no. 11, p. 19p–19p, 2005.

[5] B. N. Schenkman, “Identification of ground materials with the aid of tapping sounds and vibrations of long canes for the blind,” *Ergonomics*, vol. 29, no. 8, 1986.

[6] M. Rodgers, “A Human Factors Analysis of the Long Cane,” Ph.D. dissertation, Univ. Louisville, Louisville, KY, 1991.

[7] D. S. Kim and R. Wall Emerson, “Effect of cane length on drop-off detection performance,” *J. Vis. Impair. Blind.*, vol. 55, no. January, pp. 31–35, 2012.

[8] D. S. Kim, R. Wall Emerson, and A. Curtis, “Drop-off detection with the long cane:

Effects of different cane techniques on performance.," *J. Vis. Impair. Blind.*, vol. 103, no. 9, pp. 519–530, 2009.

[9] D. S. Kim, R. Wall Emerson, and A. Curtis, "Interaction effects of the amount of practice, preferred cane technique, and type of cane technique used on drop-off detection performance," *J. Vis. Impair. Blind.*, vol. 104, no. 8, pp. 453–463, 2010.

[10] D. Kim, R. Emerson, and A. Curtis, "Analysis of user characteristics related to drop-off detection with long cane.," *J. Rehabil. Res. Dev.*, vol. 47, no. 3, pp. 233–242, 2010.

[11] D. S. Kim, R. Wall Emerson, K. Naghshineh, and A. Auer, "Drop-off detection with the long cane: effect of cane shaft weight and rigidity on performance," Ergonomics, vol. 139, no. June, pp. 1–10, 2016.

[12] D. S. Kim and R. Wall Emerson, "Effect of cane technique on obstacle detection with the long cane," *J. Vis. Impair. Blind.*, vol. 108, no. July-August, pp. 335–340, 2014.

[13] J. A. Hesch and S. I. Roumeliotis, "An indoor localization aid for the visually impaired," *Proc. - IEEE Int. Conf. Robot. Autom.*, no. April, pp. 3545–3551, 2007.

[14] S. Gallo *et al.*, "Augmented white cane with multimodal haptic feedback," *2010 3rd IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics, BioRob 2010*, pp. 149–155, 2010.

[15] L. Kay, "A sonar aid to enhance spatial perception of the blind: Engineering design and evaluation," *Radio Electron. Eng.*, vol. 44, no. 11, p. 605, 1974.

[16] Z. O. Abu-Faraj, E. Jabbour, P. Ibrahim, and A. Ghaoui, "Design and development of a prototype rehabilitative shoes and spectacles for the blind," *2012 5th Int. Conf. Biomed. Eng. Informatics, BMEI 2012*, no. Bmei, pp. 795–799, 2012.

[17] A. Fiannaca, I. Apostolopoulous, and E. Folmer, “Headlock: A wearable navigation aid that helps blind cane users traverse large open spaces,” *Proc. 16th Int. ACM SIGACCESS Conf. Comput. Access.*, no. 1, pp. 19–26, 2014.

[18] M. Chaudhry, M. Kamran, and S. Afzal, “Speaking monuments - design and implementation of an RFID based blind friendly environment,” *2nd Int. Conf. Electr. Eng. ICEE*, no. March, 2008.

[19] Y. Kim, A. Moncada-Torres, J. Furrer, M. Riesch, and R. Gassert, “Quantification of long cane usage characteristics with the constant contact technique,” *Appl. Ergon.*, vol. 55, pp. 216–225, 2016.

[20] J. Löfvenberg and R. S. Johansson, “Regional differences and interindividual variability in sensitivity to vibration in the glabrous skin of the human hand,” *Brain Res.*, vol. 301, no. 1, pp. 65–72, 1984.

[21] A. J. Brisben, S. S. Hsiao, and K. O. Johnson, “Detection of vibration transmitted through an object grasped in the hand,” *J Neurophysiol*, vol. 81, no. 4, pp. 1548–1558, 1999.

[22] M. Morioka and M. J. Griffin, “Perception thresholds for vertical vibration at the hand, seat and foot,” *Proc. Eur. Acoust. Assoc. (Forum Acusticum)*, pp. 1577–1582, 2005.

[23] H. Oey and V. Mellert, “Vibration thresholds and equal vibration levels at the human fingertip and palm,” *Proc. ICA*, pp. 3227–3230, 2004.

[24] R. L. Klatzky, S. J. Lederman, C. Hamilton, M. Grindley, and R. H. Swendsen, “Feeling textures through a probe: effects of probe and surface geometry and exploratory factors,” *Percept. Psychophys.*, vol. 65, no. 4, pp. 613–631, 2003.

[25] S. J. Lederman, R. L. Klatzky, C. L. Hamilton, and G. I. Ramsay, "Perceiving roughness via a rigid probe: Psychophysical effects of exploration speed and mode of touch," *Haptics-e*, pp. 1–20, 1999.

[26] S. J. Lederman, R. L. Klatzky, C. Hamilton, and M. Grindley, "Perceiving surface roughness through a probe: Effects of applied force and probe diameter," *Dynamic Systems and Control Division*. pp. 69–72, 2000.

Appendix A

MATLAB and Arduino Computer Codes

```matlab
%This routine plots each plate scrape one at a time, and
%accepts click inputs on the plot. You should click once at the scrape
%beginning and once at the end. Then it plots that section, and you click
%the interface of the two plates. The output array gives the sample number
%in the first column, the three timestamps in the next 3 columns,
%and the indices in the raw file in the last three columns.
num1 = 1; %First sample number
numx = 1409; %Last sample number
%Numbers to skip, if that file does not exist
skips = [63 65 116 151 175 203 220 244 256 318 360 385 446 ...
    571 572 573 574 659 769 789 849 1037 1082 1140 1142 1154 1156 1179 ...
    1188 1200 1306 1315 1332 1337 1341 1342 1355 1377 1386];
fs = 10240; %Sample rate = 10240 Hz

EventTimes = zeros(numx-num1,7); %Initialize results array
for i = num1:numx
    %Skip files that do not exist
    if any(skips == i);
        continue
    else
        %Load SmartOffice Files
        File = strcat ('Samp', num2str(i));
        F = load (File);

        %Load raw data at tip accelerometer
        x = [F.(File)(1).x ];
        y = [F.(File)(1).y ];
        plot(x,y);
        grid on
        title (File)
        [xloc, yloc] = ginput(2);

        L = length(x);
        EventTimes(i,1) = i; %Sample Number
        if xloc(1) < 0 %To make sure there are no negative indices
            EventTimes(i,5) = 1; %Left plate starts at first index
        else
            EventTimes(i,5) = round(xloc(1)*fs + 1); %Left start index
        end
        if xloc(2)*fs + 1 > L %Make sure no indices greater than data length
            EventTimes(i,7) = L; %Right plate ends at last index
        else
            EventTimes(i,7) = round(xloc(2)*fs + 1); % Right end index
        end
        EventTimes(i,2) = x(EventTimes(i,5)); %Left start time
        EventTimes(i,4) = x(EventTimes(i,7)); %End time


plot(x(EventTimes(i,5):EventTimes(i,7)),y(EventTimes(i,5):EventTimes(i,7)));
        grid on
        title (File)
        [xloc,yloc] = ginput(1);
        EventTimes(i,6) = round(xloc(1)*fs + 1); %Middle index
        EventTimes(i,3) = x(EventTimes(i,6)); %Middle time
    end
end
```

```matlab
%This routine counts peaks in the right and left plates of each sample
%and returns the peak frequency difference and amplitude difference.
clear; clc;
num1 = 1; %First sample number
numx = 1409; %Last sample number

%Numbers to skip, if that file does not exist
skips = [63 65 116 151 175 203 220 244 256 318 360 385 446 ...
    571 572 573 574 659 769 789 849 1037 1082 1140 1142 1154 1156 1179 ...
    1188 1200 1306 1315 1332 1337 1341 1342 1355 1377 1386 3 31 49 87 97 ...
    302 356 362 363 370 384 449 478 534 545 567 569 569 765 818 831 886 ...
    893 914 1043 1087 1088 1122 1130 1149 1160 1204 1391];
fs = 10240; %Sample rate = 10240 Hz
load 'EventTimes' %File containing index numbers for each scrape
load 'PlateSizes' %Groove sizes on left(i,1) and right(i,2) plates
load 'Correct' %Subject response (0 = incorrect, 1 = correct)
for i = num1:numx
    %Skip files that do not exist
    if any(skips == i);
        continue
        else
            %Load SmartOffice Files
            File = strcat ('Samp', num2str(i));
            F = load (File);

            %tip accelerometer in field 1, handle in field 2
            x = [F.(File)(1).x ];
            y = [F.(File)(1).y ];
            %y = filter(Filter300,y); %Use to filter raw data if desired.
            %The "205" removes the last 0.02 sec of the left plate,
            %and first 0.02 sec of right plate, to cut off peak at plate
            %interface
            x1 = x(EventTimes(i,5):(EventTimes(i,6)-205));
            y1 = y(EventTimes(i,5):(EventTimes(i,6)-205));
            x2 = x((EventTimes(i,6)+205):EventTimes(i,7));
            y2 = y((EventTimes(i,6)+205):EventTimes(i,7));
            dt1 = EventTimes(i,3) - EventTimes(i,2);
            dt2 = EventTimes(i,4) - EventTimes(i,3);

            %Set threshold for prominence requirement
            y1sort = findpeaks(y1,'SortStr','descend','Npeaks',11);
            y2sort = findpeaks(y2,'SortStr','descend','Npeaks',11);
            M1 = mean(y1sort(2:11));
            M2 = mean(y2sort(2:11));

            %Find high amplitude peaks
            [pks1,locs1] = findpeaks(y1,fs,'MinPeakProminence',0.40*M1...
                ,'MinPeakDistance',0.002);
            [pks2,locs2] = findpeaks(y2,fs,'MinPeakProminence',0.40*M2...
                ,'MinPeakDistance',0.002);
            %Calculate peak rate on each side
            ratepeaks(i,1) = (length(pks1))/(locs1(length(locs1))-locs1(1));
            ratepeaks(i,2) = (length(pks2))/(locs2(length(locs2))-locs2(1));
            %Save prominence threshold
            magpeaks(i,1) = M1;
            magpeaks(i,2) = M2;
```

```
    end
end

difference(:,1) = ratepeaks(:,2) - ratepeaks(:,1); %rate difference
difference(:,2)  =  magpeaks(:,2)  -  magpeaks(:,1);  %Difference  in  threshold
amplitude
platechange = (PlateSizes(:,2) - PlateSizes(:,1));

%Find best fit for each block, removes Y intercept
load ('blocks.mat');
for j = 1:44
    first = blocks(j,1);
    last = blocks(j+1,1) - 1;
    plates = (platechange(first:last));
    Amplitude = difference(first:last,2);
   [b1, b0, rsq] = linefit(plates,Amplitude);
   fits(j,:) = [b1, b0, rsq]; %[slope y-intercept rsquared]
   difference(first:last,2)    =    difference(first:last,2)    -    fits(j,2);
%subtracts y intercept
end




function Hd = Filter300
%FILTER300 Returns a discrete-time filter object.

% MATLAB Code
% Generated by MATLAB(R) 8.6 and the Signal Processing Toolbox 7.1.
% Generated on: 27-Mar-2017 08:44:59

% Equiripple Lowpass filter designed using the FIRPM function.

% All frequency values are in Hz.
Fs = 10240;  % Sampling Frequency

Fpass = 300;              % Passband Frequency
Fstop = 1000;             % Stopband Frequency
Dpass = 0.057501127785;   % Passband Ripple
Dstop = 0.0001;           % Stopband Attenuation
dens  = 20;               % Density Factor

% Calculate the order from the parameters using FIRPMORD.
[N, Fo, Ao, W] = firpmord([Fpass, Fstop]/(Fs/2), [1 0], [Dpass, Dstop]);

% Calculate the coefficients using the FIRPM function.
b  = firpm(N, Fo, Ao, W, {dens});
Hd = dfilt.dffir(b);

% [EOF]
```

```matlab
function [b1, b0, rsq] = linefit(x,y)
%Removes bad samples, then performs linear fit and Rsquared calculation
A = [x y];
out = A;
out(any(A==0,2),:) = [];
x = out(:,1);
y = out(:,2);

p = polyfit(x,y,1);
b1 = p(1);
b0 = p(2);
yfit = polyval(p,x);
yresid = y - yfit;
SSresid = sum(yresid.^2);
SStotal = (length(y)-1)*var(y);
rsq = 1 - SSresid/SStotal;
end
```

```
// Modified by Aaron Dean
// Node 1: Connect to OptoTrack, read trigger out and start S.O.
// RFM69HCW Example Sketch
// Send serial input characters from one RFM69 node to another
// Based on RFM69 library sample code by Felix Rusu
// http://LowPowerLab.com/contact
// Modified for RFM69HCW by Mike Grusin, 4/16
// This sketch will show you the basics of using an
// RFM69HCW radio module. SparkFun's part numbers are:
// 915MHz: https://www.sparkfun.com/products/12775
// 434MHz: https://www.sparkfun.com/products/12823
// See the hook-up guide for wiring instructions:
// https://learn.sparkfun.com/tutorials/rfm69hcw-hookup-guide

// Uses the RFM69 library by Felix Rusu, LowPowerLab.com
// Original library: https://www.github.com/lowpowerlab/rfm69
// SparkFun repository: https://github.com/sparkfun/RFM69HCW_Breakout

// Include the RFM69 and SPI libraries:
#include <RFM69.h>
#include <SPI.h>

// Addresses for this node. CHANGE THESE FOR EACH NODE!
#define NETWORKID     0   // Must be the same for all nodes (0 to 255)
#define MYNODEID      1   // My node ID (0 to 255)
#define TONODEID      2   // Destination node ID (0 to 254, 255 = broadcast)

// RFM69 frequency, uncomment the frequency of your module:
//#define FREQUENCY   RF69_433MHZ
#define FREQUENCY     RF69_915MHZ

// AES encryption (or not):
#define ENCRYPT       true // Set to "true" to use encryption
#define ENCRYPTKEY    "TOPSECRETPASSWRD" // Use the same 16-byte key on all nodes

// Use ACKnowledge when sending messages (or not):
#define USEACK        true // Request ACKs or not

// Packet sent/received indicator LED (optional):
#define LED           9 // LED positive pin
#define GND           8 // LED ground pin
#define TRG           7 // Trigger for OptoTrack

// Create a library object for our RFM69HCW module:
RFM69 radio;
void setup()
```

```
{
  // Open a serial port so we can send keystrokes to the module:
  Serial.begin(9600);
  Serial.print("Node ");
  Serial.print(MYNODEID,DEC);
  Serial.println(" ready");

  // Set up the indicator LED (optional):
  pinMode(LED,OUTPUT);
  digitalWrite(LED,LOW);
  pinMode(GND,OUTPUT);
  digitalWrite(GND,LOW);
  pinMode(TRG, INPUT);
  pinMode(6,OUTPUT);
  digitalWrite(6,LOW);
  pinMode(4,OUTPUT);
  digitalWrite(4,LOW);

  // Initialize the RFM69HCW:
  radio.initialize(FREQUENCY, MYNODEID, NETWORKID);
  radio.setHighPower(); // Always use this for RFM69HCW

  // Turn on encryption if desired:
  if (ENCRYPT)
    radio.encrypt(ENCRYPTKEY);
}
void loop()
{
  // Set up a "buffer" for characters that we'll send:

  static char sendbuffer[62];
  static int sendlength = 0;
  int pinstate;
      pinstate = digitalRead(TRG);
      digitalWrite(4,pinstate);
  char input;
  // SENDING
  // In this section, we'll gather serial characters and
  // send them to the other node if we (1) get a carriage return,
  // or (2) the buffer is full (61 characters).
  // If there is any serial input, add it to the buffer.
    // If the input is a carriage return, or the buffer is full:
    if ( (digitalRead(TRG)==LOW)) // CR or buffer full
    {
      // Send the packet!
      if (USEACK)
```

```
    {
      if (radio.sendWithRetry(TONODEID, sendbuffer, sendlength))
        Serial.println("ACK received!");
      else
        Serial.println("no ACK received :(");
    }
    // If you don't need acknowledgements, just use send():
    else // don't use ACK
    {
      radio.send(TONODEID, sendbuffer, sendlength);
    }
    sendlength = 0; // reset the packet
    Blink(LED,10);

    while(digitalRead(TRG)==LOW)
    {
    }
   }
}

void Blink(byte PIN, int DELAY_MS)
// Blink an LED for a given number of ms
{
  digitalWrite(PIN,HIGH);
  digitalWrite(TRG,HIGH);
  delay(DELAY_MS);
  digitalWrite(PIN,LOW);
  digitalWrite(TRG,LOW);
}
```

```
// Modified by Aaron Dean
// Node 2: To be placed on blind participant
// RFM69HCW Example Sketch
// Send serial input characters from one RFM69 node to another
// Based on RFM69 library sample code by Felix Rusu
// http://LowPowerLab.com/contact
// Modified for RFM69HCW by Mike Grusin, 4/16
// This sketch will show you the basics of using an
// RFM69HCW radio module. SparkFun's part numbers are:
// 915MHz: https://www.sparkfun.com/products/12775
// 434MHz: https://www.sparkfun.com/products/12823

// See the hook-up guide for wiring instructions:
// https://learn.sparkfun.com/tutorials/rfm69hcw-hookup-guide
// Uses the RFM69 library by Felix Rusu, LowPowerLab.com
// Original library: https://www.github.com/lowpowerlab/rfm69
// SparkFun repository: https://github.com/sparkfun/RFM69HCW_Breakout

// Include the RFM69 and SPI libraries:
#include <RFM69.h>
#include <SPI.h>

// Addresses for this node. CHANGE THESE FOR EACH NODE!
#define NETWORKID     0   // Must be the same for all nodes (0 to 255)
#define MYNODEID      2   // My node ID (0 to 255)
#define TONODEID      1   // Destination node ID (0 to 254, 255 = broadcast)

// RFM69 frequency, uncomment the frequency of your module:
//#define FREQUENCY   RF69_433MHZ
#define FREQUENCY     RF69_915MHZ

// AES encryption (or not):
#define ENCRYPT       true // Set to "true" to use encryption
#define ENCRYPTKEY    "TOPSECRETPASSWRD" // Use the same 16-byte key on all nodes

// Use ACKnowledge when sending messages (or not):
#define USEACK        true // Request ACKs or not

// Packet sent/received indicator LED (optional):
#define LED           9 // LED positive pin
#define GND           8 // LED ground pin
#define TRG           7 // Trigger for Smart Office

// Create a library object for our RFM69HCW module:
RFM69 radio;
void setup()
```

```
{
  // Open a serial port so we can send keystrokes to the module:
  Serial.begin(9600);
  Serial.print("Node ");
  Serial.print(MYNODEID,DEC);
  Serial.println(" ready");

  // Set up the indicator LED (optional):
  pinMode(LED,OUTPUT);
  digitalWrite(LED,LOW);
  pinMode(GND,OUTPUT);
  digitalWrite(GND,LOW);
  pinMode(TRG,OUTPUT);
  digitalWrite(TRG,LOW);
  pinMode(6,OUTPUT);
  digitalWrite(6,LOW);

  // Initialize the RFM69HCW:
  radio.initialize(FREQUENCY, MYNODEID, NETWORKID);
  radio.setHighPower(); // Always use this for RFM69HCW

  // Turn on encryption if desired:
  if (ENCRYPT)
    radio.encrypt(ENCRYPTKEY);
}
void loop()
{
  // Set up a "buffer" for characters that we'll send:
  static char sendbuffer[62];
  static int sendlength = 0;

  // SENDING
  // In this section, we'll gather serial characters and
  // send them to the other node if we (1) get a carriage return,
  // or (2) the buffer is full (61 characters).

  // If there is any serial input, add it to the buffer:
  if (Serial.available() > 0)
  {
    char input = Serial.read();
    if (input != '\r') // not a carriage return
    {
      sendbuffer[sendlength] = input;
      sendlength++;
    }
```

```
  // If the input is a carriage return, or the buffer is full:
  if ((input == '\r') || (sendlength == 61)) // CR or buffer full
  {
    // Send the packet!
    Serial.print("sending to node ");
    Serial.print(TONODEID, DEC);
    Serial.print(": [");
    for (byte i = 0; i < sendlength; i++)
      Serial.print(sendbuffer[i]);
    Serial.println("]");

    // There are two ways to send packets. If you want
    // acknowledgements, use sendWithRetry():
    if (USEACK)
    {
      if (radio.sendWithRetry(TONODEID, sendbuffer, sendlength))
        Serial.println("ACK received!");
      else
        Serial.println("no ACK received :(");
    }

    // If you don't need acknowledgements, just use send():
    else // don't use ACK
    {
      radio.send(TONODEID, sendbuffer, sendlength);
    }
    sendlength = 0; // reset the packet
    Blink(LED,10);
  }
}

// RECEIVING
// In this section, we'll check with the RFM69HCW to see
// if it has received any packets:
if (radio.receiveDone()) // Got one!
{
  // Print out the information:
  Serial.print("received from node ");
  Serial.print(radio.SENDERID, DEC);
  Serial.print(": [");

  // The actual message is contained in the DATA array,
  // and is DATALEN bytes in size:
  for (byte i = 0; i < radio.DATALEN; i++)
    Serial.print((char)radio.DATA[i]);
```

```
    // RSSI is the "Receive Signal Strength Indicator",
    // smaller numbers mean higher power.
    Serial.print("], RSSI ");
    Serial.println(radio.RSSI);
    // Send an ACK if requested.
    // (You don't need this code if you're not using ACKs.
    if (radio.ACKRequested())
    {
      radio.sendACK();
      Serial.println("ACK sent");
    }
    Blink(LED,10);
  }
}

void Blink(byte PIN, int DELAY_MS)
// Blink an LED for a given number of ms
{
  digitalWrite(PIN,HIGH);
  digitalWrite(TRG,HIGH);
  delay(DELAY_MS);
  digitalWrite(PIN,LOW);
  digitalWrite(TRG,LOW);
}
```

Appendix B

Complete Texture Discrimination Experiment Results

Participant 1, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1	5.5	3.5	Y	-20.768	N	5.875	Y
2	3.5	2.5	Y	28.288	Y	-11.206	Y
3	3.5	4	Y	-	-	-	-
4	3.5	4.5	Y	-28.020	Y	32.213	Y
5	4	3.5	Y	21.935	Y	-34.552	Y
6	3.5	2	Y	51.958	Y	-0.099	Y
7	4.5	3.5	N	-19.571	N	34.128	N
8	3.5	3	N	-5.303	N	37.661	N
9	2	3.5	Y	-80.946	Y	125.610	Y
10	1.5	3.5	Y	-97.149	Y	80.377	Y
11	5.5	3.5	Y	7.229	Y	-94.507	Y
12	3.5	4.5	Y	-9.621	Y	54.492	Y
13	2.5	3.5	Y	-13.374	Y	-20.792	N
14	3.5	2	Y	45.273	Y	-12.326	Y
15	3	3.5	Y	-56.211	Y	48.216	Y
16	5	3.5	Y	25.498	Y	-127.003	Y
17	2.5	3.5	Y	-29.935	Y	15.655	N
18	2	3.5	Y	-68.390	Y	22.145	Y
19	3	3.5	N	-14.638	Y	-11.817	N
20	1.5	3.5	Y	-94.107	Y	35.731	Y
21	3.5	5	Y	-35.207	Y	101.964	Y
22	3.5	2.5	Y	25.437	Y	9.892	Y
23	3.5	3	Y	17.580	Y	-2.057	Y
24	4	3.5	N	5.827	Y	-18.220	Y
25	5	3.5	Y	17.540	Y	-92.520	Y
26	4.5	3.5	N	-36.177	N	32.659	N
27	3.5	5.5	Y	-41.154	Y	172.026	Y
28	3.5	1.5	Y	35.478	Y	-43.252	Y
29	3.5	5	Y	-32.192	Y	115.533	Y
30	3.5	5.5	Y	-36.373	Y	184.853	Y
31	3.5	4	Y	-	-	-	-
32	3.5	1.5	Y	80.429	Y	-38.277	Y

Participant 1, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
33	2.5	3.5	Y	-141.16	Y	361.81	Y
34	3.5	5.5	Y	-89.54	Y	246.96	Y
35	3.5	3	Y	21.37	Y	51.20	Y
36	4	3.5	N	-39.63	N	134.76	Y
37	3.5	2.5	Y	107.46	Y	-126.24	Y
38	3.5	5.5	Y	-46.11	Y	284.52	Y
39	5	3.5	Y	-13.44	N	180.13	N
40	2.5	3.5	N	12.60	N	79.49	N
41	3.5	2	Y	91.80	Y	42.12	Y
42	3.5	4.5	Y	11.66	N	117.91	N
43	2	3.5	Y	-20.83	Y	212.33	Y
44	4.5	3.5	N	20.65	Y	134.15	Y

45	3.5	1.5	Y	73.31	Y	28.03	Y
46	3.5	4	Y	-42.62	Y	429.99	Y
47	1.5	3.5	Y	-77.50	Y	225.43	Y
48	1.5	3.5	Y	-108.18	Y	303.99	Y
49	4	3.5	Y	-	-	-	-
50	3	3.5	Y	-40.52	Y	246.64	Y
51	3.5	5	Y	2.94	N	323.52	Y
52	5	3.5	Y	12.27	Y	41.40	Y
53	3.5	4.5	N	31.90	N	62.29	N
54	3.5	2	Y	140.61	Y	-72.83	Y
55	4.5	3.5	N	10.72	Y	126.41	Y
56	3.5	2.5	Y	41.38	Y	22.63	Y
57	5.5	3.5	Y	37.23	Y	3.48	Y
58	2	3.5	Y	-84.40	Y	155.48	Y
59	3	3.5	N	17.71	N	147.59	Y
60	3.5	4	Y	-39.86	Y	288.24	Y
61	3.5	1.5	Y	172.35	Y	-50.09	Y
62	3.5	5	Y	25.18	N	115.89	N
63	3.5	3	Y	-	-	-	-
64	5.5	3.5	Y	29.07	Y	26.26	Y

Participant 1, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
65	3.5	2	Y	-	-	-	-
66	4.5	3.5	Y	11.71	Y	32.30	Y
67	2	3.5	Y	-135.39	Y	258.05	Y
68	3.5	4.5	Y	4.98	N	74.26	Y
69	2	3.5	Y	-31.28	Y	82.61	Y
70	3.5	5.5	Y	-44.06	Y	200.68	Y
71	3.5	4	Y	-10.46	Y	82.45	Y
72	5	3.5	Y	20.22	Y	-92.41	Y
73	3.5	3	N	11.50	Y	65.45	N
74	3.5	5.5	Y	-25.93	Y	173.65	Y
75	3.5	2.5	Y	58.42	Y	37.70	Y
76	3.5	5	Y	7.21	N	114.33	Y
77	5	3.5	Y	34.49	Y	-83.37	Y
78	3.5	5	Y	-19.96	Y	106.70	Y
79	3.5	2.5	Y	75.60	Y	-23.57	Y
80	1.5	3.5	Y	-32.61	Y	100.38	Y
81	5.5	3.5	Y	47.77	Y	-51.02	Y
82	3.5	1.5	Y	60.11	Y	-71.87	Y
83	5.5	3.5	Y	47.20	Y	-43.28	Y
84	3	3.5	N	7.02	N	-15.12	N
85	4	3.5	Y	43.28	Y	-68.34	Y
86	2.5	3.5	N	-21.55	Y	54.54	Y
87	3.5	1.5	Y	-	-	-	-
88	4.5	3.5	Y	34.79	Y	76.98	N
89	3.5	2	Y	58.18	Y	-21.16	Y
90	1.5	3.5	Y	-126.77	Y	165.31	Y
91	3.5	4	Y	7.24	N	95.42	Y
92	3	3.5	N	22.60	N	18.79	N
93	3.5	4.5	Y	27.60	N	2.79	N
94	2.5	3.5	N	70.40	N	-20.63	N

95	3.5	3	Y	3.40	Y	-15.19	Y
96	4	3.5	Y	30.01	Y	85.78	N

Participant 1, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
97	3.5	5.5	Y	-	-	-	-
98	3	3.5	Y	-67.40	Y	496.51	Y
99	2	3.5	Y	-22.42	Y	240.36	Y
100	3	3.5	Y	-40.89	Y	390.96	Y
101	3.5	2	Y	120.57	Y	-132.81	Y
102	4.5	3.5	Y	20.12	Y	222.95	N
103	3.5	4	Y	80.03	N	77.60	N
104	3.5	5	Y	-29.43	Y	224.54	Y
105	4	3.5	N	8.61	Y	278.77	N
106	5	3.5	Y	14.83	Y	279.45	N
107	3.5	1.5	Y	148.04	Y	-84.49	Y
108	3.5	4	Y	-30.41	Y	386.41	Y
109	3.5	5	Y	20.27	N	263.90	Y
110	3.5	2.5	Y	132.81	Y	-129.28	Y
111	3.5	5.5	Y	-38.57	Y	423.46	Y
112	5	3.5	Y	36.77	Y	-7.53	Y
113	5.5	3.5	Y	60.19	Y	-47.96	Y
114	3.5	2	Y	157.27	Y	-277.12	Y
115	2	3.5	Y	-105.77	Y	467.36	Y
116	2.5	3.5	Y	-	-	-	-
117	4	3.5	N	12.74	Y	381.08	N
118	3.5	1.5	Y	99.74	Y	11.62	Y
119	5.5	3.5	N	31.38	Y	246.59	N
120	3.5	4.5	Y	14.63	N	313.97	Y
121	1.5	3.5	Y	-133.81	Y	708.33	Y
122	3.5	3	Y	143.51	Y	122.49	Y
123	1.5	3.5	Y	-94.64	Y	372.31	Y
124	3.5	3	Y	81.78	Y	128.78	Y
125	2.5	3.5	Y	-81.57	Y	356.08	Y
126	3.5	4.5	N	77.56	N	-16.79	N
127	4.5	3.5	N	-53.30	N	564.84	N
128	3.5	2.5	Y	45.22	Y	18.18	Y

Participant 2, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
129	3.5	4	N	-56.51	Y	409.07	Y
130	3.5	2	Y	86.49	Y	57.38	Y
131	4	3.5	Y	58.65	Y	194.81	Y
132	3.5	4.5	N	11.49	N	86.66	N
133	4.5	3.5	Y	25.50	Y	129.87	Y
134	1.5	3.5	Y	-126.89	Y	559.40	Y
135	3.5	4.5	N	-23.79	Y	374.38	Y
136	3	3.5	Y	-61.74	Y	332.55	Y

137	5	3.5	Y	44.87	Y	170.81	Y
138	3.5	5.5	Y	15.64	N	388.15	Y
139	5	3.5	Y	20.25	Y	146.00	Y
140	3.5	1.5	Y	120.29	Y	-68.60	Y
141	2	3.5	Y	-121.55	Y	430.54	Y
142	5.5	3.5	Y	40.97	Y	62.26	Y
143	3.5	2.5	Y	147.98	Y	73.51	Y
144	3.5	1.5	Y	166.48	Y	-11.33	Y
145	1.5	3.5	Y	-60.27	Y	373.16	Y
146	3.5	2	Y	131.60	Y	102.45	Y
147	3.5	5.5	Y	-21.31	Y	562.07	Y
148	3.5	4	Y	-50.93	Y	649.92	Y
149	3.5	5	Y	10.06	N	599.12	Y
150	2	3.5	Y	-19.47	Y	151.43	N
151	3.5	3	Y	-	-	-	-
152	3	3.5	Y	29.80	N	132.83	N
153	3.5	2.5	Y	126.62	Y	64.04	Y
154	3.5	3	Y	100.82	Y	152.43	Y
155	5.5	3.5	Y	24.76	Y	143.34	Y
156	2.5	3.5	Y	-24.06	Y	272.00	Y
157	4.5	3.5	N	16.96	Y	395.07	N
158	3.5	5	N	-28.30	Y	574.03	Y
159	4	3.5	N	43.36	Y	338.28	N
160	2.5	3.5	N	-24.47	Y	415.18	Y

Participant 2, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
161	2	3.5	Y	-96.98	Y	337.13	Y
162	3.5	3	N	4.16	Y	239.99	N
163	3.5	2	Y	155.76	Y	2.43	Y
164	4.5	3.5	Y	-3.89	N	80.55	Y
165	3.5	4	Y	-16.06	Y	219.88	Y
166	3.5	5.5	Y	-7.06	Y	288.92	Y
167	3	3.5	Y	11.99	N	129.36	Y
168	3.5	3	N	25.84	Y	64.05	Y
169	1.5	3.5	Y	-118.16	Y	249.16	Y
170	3.5	5.5	Y	-2.66	Y	241.88	Y
171	5.5	3.5	Y	49.47	Y	21.29	Y
172	2.5	3.5	Y	-35.20	Y	98.77	N
173	3.5	4.5	N	47.74	N	-17.99	N
174	4	3.5	Y	16.32	Y	89.83	Y
175	5	3.5	Y	-	-	-	-
176	3.5	4.5	N	8.25	N	21.99	N
177	2.5	3.5	Y	-25.83	Y	125.08	Y
178	3.5	5	Y	10.01	N	242.94	Y
179	4.5	3.5	Y	42.91	Y	204.74	N
180	3.5	1.5	Y	92.05	Y	-57.36	Y
181	4	3.5	Y	1.43	Y	144.64	N
182	2	3.5	Y	-30.47	Y	63.05	N
183	3.5	2.5	Y	43.08	Y	-15.19	Y
184	3.5	4	Y	-21.23	Y	211.11	Y
185	3.5	5	Y	-1.50	Y	197.95	Y
186	3	3.5	Y	-31.44	Y	213.32	Y

187	3.5	2	Y	134.19	Y	-115.03	Y
188	5.5	3.5	Y	27.85	Y	81.06	Y
189	3.5	2.5	Y	47.71	Y	-26.22	Y
190	1.5	3.5	Y	-77.38	Y	105.38	N
191	3.5	1.5	Y	80.03	Y	-10.29	Y
192	5	3.5	Y	26.82	Y	90.25	Y

Participant 2, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
193	3.5	2	Y	85.48	Y	134.03	Y
194	3.5	5	N	55.73	N	300.63	N
195	2	3.5	Y	118.62	N	142.18	N
196	3.5	5.5	Y	-19.58	Y	494.63	Y
197	5.5	3.5	Y	89.18	Y	-6.51	Y
198	3.5	5.5	Y	-12.09	Y	699.01	Y
199	5.5	3.5	Y	64.74	Y	262.15	Y
200	5	3.5	Y	31.08	Y	264.58	Y
201	3.5	4.5	N	73.23	N	335.96	N
202	3.5	4	Y	-18.53	Y	387.99	Y
203	1.5	3.5	Y	-	-	-	-
204	3.5	1.5	Y	140.59	Y	-88.60	Y
205	4.5	3.5	N	19.93	Y	315.79	Y
206	3.5	3	Y	19.86	Y	463.30	N
207	2.5	3.5	Y	-135.35	Y	637.04	Y
208	3.5	4.5	N	-23.72	Y	551.05	Y
209	3.5	4	Y	-24.54	Y	769.93	Y
210	1.5	3.5	Y	-46.34	Y	470.42	Y
211	4	3.5	N	2.86	Y	311.04	Y
212	2	3.5	Y	-84.13	Y	602.01	Y
213	3.5	2.5	Y	155.95	Y	-130.01	Y
214	3.5	5	Y	-54.22	Y	705.82	Y
215	3.5	3	Y	131.26	Y	112.44	Y
216	3	3.5	Y	-50.82	Y	528.11	Y
217	2.5	3.5	Y	19.04	N	573.46	Y
218	5	3.5	Y	56.09	Y	267.07	Y
219	4	3.5	N	-10.43	N	629.05	N
220	3	3.5	N	-	-	-	-
221	3.5	2.5	Y	143.20	Y	125.22	Y
222	4.5	3.5	N	69.27	Y	274.16	Y
223	3.5	2	Y	18.83	Y	317.31	Y
224	3.5	1.5	Y	87.68	Y	9.96	Y

Participant 2, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
225	3.5	4	N	-70.60	Y	196.14	Y
226	3.5	3	Y	-9.85	N	18.12	Y
227	5	3.5	Y	59.76	Y	-81.55	Y
228	2	3.5	Y	-51.06	Y	26.95	N

229	2.5	3.5	Y	-14.25	Y	93.60	Y
230	3.5	4.5	N	9.38	N	103.02	Y
231	3.5	1.5	Y	184.81	Y	-118.80	Y
232	3.5	5	Y	-116.46	Y	277.30	Y
233	4	3.5	N	16.69	Y	16.52	Y
234	3.5	2	Y	-55.71	N	90.94	N
235	4.5	3.5	Y	24.59	Y	54.23	Y
236	3.5	2.5	Y	65.21	Y	-92.67	Y
237	3.5	5.5	Y	-2.16	Y	132.64	Y
238	4	3.5	Y	38.70	Y	11.18	Y
239	5.5	3.5	Y	57.41	Y	67.50	Y
240	5.5	3.5	Y	77.05	Y	-131.34	Y
241	4.5	3.5	Y	51.38	Y	61.65	Y
242	3.5	5	Y	-16.49	Y	187.35	Y
243	3.5	5.5	Y	1.82	N	32.36	N
244	3.5	2.5	Y	-	-	-	-
245	3	3.5	Y	19.53	N	10.67	N
246	2.5	3.5	Y	-40.53	Y	119.00	Y
247	3	3.5	N	-15.01	Y	51.77	N
248	3.5	3	N	23.43	Y	153.20	N
249	3.5	2	Y	63.66	Y	1.18	Y
250	1.5	3.5	Y	-84.18	Y	263.40	Y
251	3.5	1.5	Y	60.06	Y	-40.55	Y
252	3.5	4	Y	-77.64	Y	238.66	Y
253	1.5	3.5	Y	-67.69	Y	283.07	Y
254	2	3.5	Y	-13.14	Y	197.34	Y
255	3.5	4.5	N	35.21	N	-29.09	N
256	5	3.5	Y	-	-	-	-

Participant 3, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
257	1.5	3.5	Y	-136.66	Y	207.40	Y
258	3.5	2	Y	107.79	Y	-76.78	Y
259	3	3.5	Y	44.49	N	-72.47	N
260	2.5	3.5	Y	-59.74	Y	91.66	Y
261	4	3.5	Y	-18.13	N	8.44	Y
262	3.5	2	Y	87.70	Y	-26.67	Y
263	3	3.5	N	-39.39	Y	90.54	Y
264	3.5	5	Y	-66.70	Y	187.29	Y
265	3.5	5	N	-27.20	Y	174.48	Y
266	3.5	1.5	Y	61.44	Y	19.68	Y
267	4.5	3.5	Y	14.94	Y	53.24	N
268	3.5	1.5	Y	112.09	Y	-21.49	Y
269	3.5	4.5	Y	-35.45	Y	41.92	N
270	3.5	3	Y	-3.88	N	53.28	N
271	3.5	2.5	Y	47.04	Y	-39.11	Y
272	2	3.5	Y	-77.12	Y	107.68	Y
273	2	3.5	N	0.03	N	38.23	N
274	5.5	3.5	Y	39.18	Y	-93.63	Y
275	5	3.5	Y	47.61	Y	-71.24	Y
276	4.5	3.5	Y	37.41	Y	-5.78	Y
277	3.5	4	Y	-35.20	Y	91.25	Y
278	1.5	3.5	Y	-103.32	Y	248.02	Y

279	5.5	3.5	Y	47.75	Y	-83.61	Y
280	3.5	5.5	Y	-24.30	Y	89.00	Y
281	3.5	5.5	Y	-75.40	Y	258.81	Y
282	5	3.5	Y	-2.28	N	-39.62	Y
283	3.5	3	Y	-12.82	N	64.81	N
284	2.5	3.5	Y	-55.22	Y	78.56	Y
285	3.5	4.5	N	-21.85	Y	36.82	N
286	3.5	4	Y	-40.06	Y	83.76	Y
287	3.5	2.5	Y	64.75	Y	-24.94	Y
288	4	3.5	Y	81.12	Y	-65.62	Y

Participant 3, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
289	5	3.5	N	-66.93	N	261.93	N
290	1.5	3.5	Y	-149.96	Y	323.30	Y
291	3.5	2.5	Y	29.42	Y	50.16	Y
292	2	3.5	Y	-144.19	Y	242.60	Y
293	3.5	5	N	4.17	N	68.17	N
294	5.5	3.5	Y	9.40	Y	59.42	Y
295	3.5	3	N	4.36	Y	-14.72	Y
296	3	3.5	N	-92.10	Y	449.06	Y
297	3.5	1.5	Y	54.38	Y	-106.59	Y
298	3.5	3	N	-55.64	N	199.57	N
299	5.5	3.5	Y	-0.62	N	-165.69	Y
300	3.5	5.5	N	-15.31	Y	-40.51	N
301	4.5	3.5	N	-73.55	N	205.64	N
302	3.5	5	Y	-	-	-	-
303	1.5	3.5	Y	-174.98	Y	415.79	Y
304	3	3.5	Y	-107.05	Y	273.42	Y
305	3.5	4.5	N	63.89	N	6.46	N
306	2.5	3.5	Y	-94.19	Y	183.22	Y
307	4	3.5	Y	-60.25	N	193.54	N
308	3.5	2	Y	1.81	Y	195.02	N
309	3.5	4	Y	-10.66	Y	234.80	Y
310	3.5	5.5	N	23.44	N	93.05	N
311	2	3.5	Y	-154.51	Y	301.48	Y
312	3.5	4	N	-20.96	Y	203.77	Y
313	3.5	4.5	N	-8.54	Y	86.24	N
314	4	3.5	N	4.72	Y	81.15	Y
315	5	3.5	Y	-7.04	N	101.63	Y
316	3.5	2.5	N	23.59	Y	-85.56	Y
317	2.5	3.5	Y	-26.43	Y	229.62	Y
318	3.5	2	Y	-	-	-	-
319	3.5	1.5	Y	48.56	Y	-47.01	Y
320	4.5	3.5	Y	-51.73	N	127.15	Y

Participant 3, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct

321	3.5	1.5	Y	100.57	Y	-108.50	Y
322	3.5	5.5	Y	-38.85	Y	149.94	Y
323	3.5	2	Y	38.75	Y	-37.47	Y
324	3	3.5	N	-22.48	Y	51.00	Y
325	3.5	4	Y	-13.43	Y	104.69	Y
326	3.5	4.5	N	3.95	N	44.54	Y
327	3.5	3	N	32.04	Y	4.90	Y
328	4.5	3.5	Y	-0.80	N	55.86	N
329	3.5	2.5	Y	51.70	Y	-44.04	Y
330	3.5	1.5	Y	101.94	Y	-28.74	Y
331	1.5	3.5	Y	-82.35	Y	98.70	Y
332	5.5	3.5	Y	42.30	Y	-39.17	Y
333	3.5	2	Y	63.72	Y	-39.34	Y
334	3.5	5	Y	-6.97	Y	120.77	Y
335	3.5	5	Y	-11.69	Y	112.46	Y
336	3.5	3	N	-6.18	N	65.17	N
337	3	3.5	N	20.70	N	18.48	N
338	5	3.5	Y	29.49	Y	-46.89	Y
339	3.5	4.5	N	-8.23	Y	49.81	Y
340	2	3.5	Y	-105.45	Y	145.42	Y
341	3.5	5.5	Y	-37.54	Y	157.74	Y
342	2	3.5	N	-47.55	Y	92.03	Y
343	5.5	3.5	Y	22.62	Y	-15.95	Y
344	3.5	4	Y	-0.85	Y	47.00	Y
345	2.5	3.5	Y	-8.17	Y	36.74	N
346	3.5	2.5	Y	59.36	Y	-25.96	Y
347	5	3.5	Y	27.96	Y	-20.66	Y
348	4.5	3.5	Y	13.48	Y	19.36	Y
349	1.5	3.5	Y	-110.01	Y	143.90	Y
350	4	3.5	Y	11.20	Y	25.79	Y
351	2.5	3.5	Y	-62.98	Y	92.87	Y
352	4	3.5	Y	20.11	Y	-3.39	Y

Participant 3, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
353	3.5	5	Y	-24.09	Y	189.06	Y
354	1.5	3.5	Y	-65.45	Y	177.66	Y
355	3.5	4.5	N	25.57	N	34.95	N
356	3.5	5.5	Y	-	-	-	-
357	3.5	1.5	Y	29.02	Y	-83.11	Y
358	2.5	3.5	N	-12.73	Y	52.21	N
359	3	3.5	N	-35.94	Y	84.48	Y
360	3	3.5	N	-	-	-	-
361	3.5	4.5	N	-3.28	Y	68.42	N
362	3.5	2.5	Y	-	-	-	-
363	4.5	3.5	Y	-	-	-	-
364	3.5	3	N	-7.84	N	112.81	N
365	2	3.5	Y	-131.26	Y	338.44	Y
366	3.5	1.5	Y	85.48	Y	-42.38	Y
367	3.5	3	Y	4.57	Y	22.49	Y
368	3.5	5.5	Y	8.26	N	183.65	Y
369	4.5	3.5	Y	-7.80	N	68.28	Y
370	5	3.5	N	-	-	-	-

371	2	3.5	N	-58.67	Y	95.35	Y
372	3.5	2.5	Y	52.44	Y	-107.35	Y
373	5	3.5	Y	8.90	Y	-6.59	Y
374	2.5	3.5	Y	-67.04	Y	166.35	Y
375	3.5	2	Y	-10.21	N	77.59	Y
376	1.5	3.5	Y	-85.91	Y	147.54	Y
377	4	3.5	Y	-9.55	N	139.22	N
378	3.5	2	Y	13.14	Y	24.41	Y
379	3.5	4	Y	-35.99	Y	148.71	Y
380	3.5	5	Y	22.26	N	157.41	Y
381	5.5	3.5	Y	4.36	Y	38.28	Y
382	4	3.5	N	35.78	Y	69.65	Y
383	3.5	4	Y	-3.03	Y	121.43	Y
384	5.5	3.5	Y	-	-	-	-

Participant 4, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
385	2	3.5	Y	-	-	-	-
386	3.5	2.5	Y	62.16	Y	-58.33	Y
387	3.5	3	N	22.61	Y	227.44	N
388	1.5	3.5	Y	-57.16	Y	149.91	Y
389	3.5	5	Y	-8.15	Y	232.02	Y
390	3.5	4	Y	-0.85	Y	252.38	Y
391	5.5	3.5	Y	51.15	Y	-9.69	Y
392	5.5	3.5	Y	25.02	Y	71.11	Y
393	4.5	3.5	Y	60.34	Y	24.35	Y
394	3.5	5.5	Y	-9.30	Y	303.41	Y
395	3.5	1.5	Y	34.75	Y	183.22	N
396	3.5	1.5	Y	91.50	Y	-18.09	Y
397	2	3.5	Y	-64.30	Y	177.49	Y
398	2.5	3.5	Y	-100.15	Y	268.72	Y
399	5	3.5	Y	30.17	Y	-46.96	Y
400	3.5	5.5	Y	-37.27	Y	279.49	Y
401	3	3.5	Y	-2.99	Y	116.31	N
402	3.5	3	N	4.24	Y	163.43	N
403	5	3.5	Y	3.40	Y	-29.58	Y
404	3.5	2.5	Y	167.68	Y	-114.15	Y
405	1.5	3.5	Y	-83.32	Y	242.72	Y
406	3.5	4.5	Y	-5.58	Y	109.56	N
407	3.5	4.5	Y	-19.64	Y	205.38	Y
408	3.5	4	Y	-20.39	Y	265.23	Y
409	3.5	5	Y	0.71	N	226.69	Y
410	3	3.5	Y	19.71	N	220.38	Y
411	4	3.5	Y	64.84	Y	143.46	N
412	4.5	3.5	Y	25.74	Y	250.30	N
413	4	3.5	N	65.74	Y	177.10	N
414	3.5	2	Y	95.76	Y	85.57	Y
415	2.5	3.5	Y	84.55	N	193.43	Y
416	3.5	2	Y	140.41	Y	-51.13	Y

Participant 4, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
417	3.5	3	Y	-28.88	N	29.63	N
418	4	3.5	Y	0.60	Y	28.15	N
419	3.5	5.5	Y	-29.27	Y	81.51	Y
420	5	3.5	Y	33.34	Y	-67.32	Y
421	3.5	1.5	Y	92.41	Y	-92.24	Y
422	2	3.5	Y	-54.89	Y	78.06	Y
423	3	3.5	Y	-49.07	Y	62.76	Y
424	2.5	3.5	Y	-22.93	Y	49.78	Y
425	2	3.5	Y	-64.90	Y	78.74	Y
426	3	3.5	Y	-25.59	Y	51.55	Y
427	3.5	5	Y	-1.51	Y	33.74	Y
428	3.5	2.5	N	10.36	Y	7.83	Y
429	4	3.5	Y	12.67	Y	-22.70	Y
430	3.5	5	Y	-41.41	Y	73.04	Y
431	3.5	2.5	N	-8.06	N	9.49	Y
432	3.5	2	Y	20.35	Y	-37.96	Y
433	3.5	4.5	Y	-1.36	Y	-1.53	N
434	3.5	4	Y	-30.83	Y	67.10	Y
435	1.5	3.5	Y	-76.16	Y	78.13	Y
436	3.5	4	Y	-33.25	Y	57.23	Y
437	1.5	3.5	Y	-43.01	Y	66.99	Y
438	2.5	3.5	Y	-62.70	Y	66.41	Y
439	3.5	1.5	N	81.13	Y	-42.93	Y
440	5	3.5	Y	28.37	Y	-52.77	Y
441	3.5	5.5	Y	-12.01	Y	45.74	Y
442	5.5	3.5	Y	16.77	Y	-67.65	Y
443	3.5	3	Y	10.21	Y	-17.56	Y
444	5.5	3.5	Y	22.95	Y	-56.39	Y
445	4.5	3.5	N	4.71	Y	-0.46	Y
446	3.5	2	N	-	-	-	-
447	4.5	3.5	N	-3.86	N	23.93	N
448	3.5	4.5	Y	11.15	N	31.77	Y

Participant 4, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
449	3.5	3	Y	-	-	-	-
450	3.5	5.5	Y	-10.24	Y	168.49	Y
451	3.5	2.5	Y	37.74	Y	33.84	Y
452	5	3.5	Y	37.18	Y	-73.64	Y
453	3	3.5	Y	-31.19	Y	118.85	Y
454	3.5	2.5	Y	33.42	Y	-30.58	Y
455	2.5	3.5	Y	-7.67	Y	88.64	Y
456	3.5	4.5	N	56.36	N	-10.55	N
457	2	3.5	Y	-53.44	Y	117.03	Y
458	4	3.5	Y	31.65	Y	-35.49	Y
459	3.5	3	N	-2.97	N	121.07	N
460	3.5	1.5	Y	43.68	Y	39.37	Y

461	4.5	3.5	N	-14.61	N	91.87	N
462	4.5	3.5	N	-11.14	N	100.11	N
463	2.5	3.5	Y	-28.75	Y	73.00	Y
464	3.5	2	Y	29.74	Y	-28.39	Y
465	3.5	5.5	Y	-15.23	Y	214.16	Y
466	3	3.5	Y	-6.03	Y	71.05	Y
467	4	3.5	N	8.08	Y	78.54	N
468	2	3.5	N	-59.21	Y	94.15	Y
469	3.5	4.5	N	28.94	N	7.23	N
470	5.5	3.5	N	-50.55	N	99.73	N
471	1.5	3.5	N	-50.33	Y	86.25	Y
472	5.5	3.5	Y	6.53	Y	-60.35	Y
473	3.5	5	Y	-18.05	Y	238.86	Y
474	1.5	3.5	Y	-58.44	Y	195.66	Y
475	3.5	2	Y	61.70	Y	-17.46	Y
476	3.5	5	N	20.84	N	96.13	Y
477	3.5	1.5	Y	100.80	Y	-65.67	Y
478	5	3.5	N	-	-	-	-
479	3.5	4	N	-0.14	Y	133.57	Y
480	3.5	4	Y	-19.10	Y	256.67	Y

Participant 4, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
481	3.5	1.5	Y	49.26	Y	-85.55	Y
482	3.5	4	Y	-22.32	Y	76.56	Y
483	3.5	2	Y	48.23	Y	-44.79	Y
484	4	3.5	Y	5.45	Y	-43.21	Y
485	3.5	4.5	Y	-7.16	Y	52.79	N
486	3.5	2.5	Y	33.95	Y	-12.14	Y
487	5	3.5	Y	31.60	Y	-8.74	Y
488	4.5	3.5	N	3.11	Y	116.13	N
489	2.5	3.5	Y	-23.28	Y	75.64	Y
490	3.5	5.5	Y	-39.52	Y	155.87	Y
491	2.5	3.5	Y	-4.68	Y	21.07	N
492	3.5	2	Y	100.17	Y	-105.95	Y
493	3.5	5	Y	13.31	N	87.95	Y
494	4.5	3.5	Y	19.12	Y	33.61	Y
495	3.5	1.5	Y	85.53	Y	-9.52	Y
496	3.5	2.5	Y	1.67	Y	24.96	Y
497	3.5	4.5	Y	-47.29	Y	102.08	Y
498	3.5	5	Y	-68.09	Y	191.75	Y
499	5.5	3.5	Y	31.01	Y	-4.03	Y
500	3	3.5	Y	-31.83	Y	79.99	Y
501	3.5	5.5	Y	-45.00	Y	211.73	Y
502	5.5	3.5	Y	36.53	Y	-36.77	Y
503	3	3.5	Y	-7.25	Y	76.51	Y
504	5	3.5	N	11.14	Y	7.15	Y
505	2	3.5	Y	-60.51	Y	149.46	Y
506	1.5	3.5	Y	-110.70	Y	202.49	Y
507	4	3.5	Y	-4.35	N	90.04	N
508	1.5	3.5	Y	21.93	N	-8.84	N
509	3.5	3	Y	3.44	Y	32.23	Y
510	2	3.5	Y	-63.37	Y	182.29	Y

511	3.5	3	N	-7.52	N	58.32	N
512	3.5	4	Y	-8.04	Y	161.12	Y

Participant 5, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
513	4.5	3.5	N	-45.09	N	45.40	N
514	3.5	2	Y	37.82	Y	-100.88	Y
515	3.5	5	Y	19.76	N	27.43	Y
516	3.5	4	N	-27.23	Y	17.10	Y
517	1.5	3.5	Y	-123.57	Y	86.25	Y
518	3.5	1.5	Y	142.24	Y	-58.90	Y
519	3.5	4	Y	-36.45	Y	49.51	Y
520	2	3.5	Y	-41.25	Y	45.78	Y
521	1.5	3.5	Y	-105.61	Y	88.23	Y
522	5.5	3.5	Y	14.58	Y	19.61	N
523	3.5	3	Y	39.44	Y	-37.73	Y
524	3.5	2	Y	11.36	Y	-20.44	Y
525	2.5	3.5	Y	-47.29	Y	12.15	N
526	4	3.5	Y	26.15	Y	-26.23	Y
527	3.5	2.5	Y	63.04	Y	-28.75	Y
528	3.5	2.5	Y	18.65	Y	12.00	Y
529	5	3.5	Y	27.08	Y	-4.10	Y
530	2	3.5	Y	-40.07	Y	11.51	N
531	3.5	4.5	N	-14.49	Y	33.38	Y
532	3.5	1.5	Y	18.37	Y	-20.35	Y
533	3	3.5	Y	-47.29	Y	27.64	Y
534	3.5	5.5	N	-	-	-	-
535	5	3.5	Y	16.00	Y	-10.08	Y
536	3.5	4.5	N	-4.69	Y	37.97	Y
537	3.5	5	N	-15.74	Y	-9.88	N
538	3	3.5	Y	-44.04	Y	24.35	Y
539	4.5	3.5	Y	-0.19	N	3.58	Y
540	4	3.5	Y	31.59	Y	-21.00	Y
541	2.5	3.5	N	-6.28	Y	-2.36	N
542	3.5	5.5	Y	-71.72	Y	190.75	Y
543	5.5	3.5	Y	-23.84	N	27.59	N
544	3.5	3	Y	1.90	Y	48.18	N

Participant 5, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
545	3.5	5	N	-	-	-	-
546	1.5	3.5	N	-42.72	Y	76.47	Y
547	3	3.5	N	-69.72	Y	24.41	Y
548	3.5	1.5	Y	-29.58	N	2.82	Y
549	3.5	2	Y	78.09	Y	-41.32	Y
550	3.5	4.5	Y	15.00	N	15.27	N
551	3	3.5	Y	-8.47	Y	27.79	Y
552	3.5	4	N	-63.57	Y	137.68	Y

553	5	3.5	Y	-10.19	N	37.02	N
554	3.5	5.5	Y	-7.92	Y	9.23	N
555	3.5	2.5	Y	-47.81	N	75.81	N
556	3.5	2	Y	84.90	Y	-72.92	Y
557	4	3.5	Y	69.75	Y	-60.18	Y
558	2	3.5	N	-1.17	Y	21.72	N
559	3.5	1.5	Y	137.12	Y	-137.42	Y
560	1.5	3.5	Y	-177.67	Y	156.35	Y
561	4	3.5	Y	-28.20	N	3.02	Y
562	2.5	3.5	Y	-21.25	Y	28.42	Y
563	3.5	4.5	N	-32.03	Y	125.71	Y
564	3.5	5	N	-31.97	Y	34.94	Y
565	3.5	2.5	N	8.24	Y	-132.26	Y
566	2.5	3.5	N	-48.87	Y	34.35	Y
567	4.5	3.5	Y	-	-	-	-
568	3.5	3	Y	-146.06	N	56.14	N
569	3.5	3	Y	-	-	-	-
570	3.5	4	N	-50.51	Y	142.24	Y
571	5.5	3.5	Y	-	-	-	-
572	5.5	3.5	Y	-	-	-	-
573	2	3.5	N	-	-	-	-
574	3.5	5.5	N	-	-	-	-
575	5	3.5	Y	39.40	Y	-11.91	Y
576	4.5	3.5	Y	-120.11	N	57.22	N

Participant 5, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
577	1.5	3.5	Y	-120.45	Y	60.48	Y
578	3.5	2.5	Y	39.88	Y	74.30	N
579	5	3.5	Y	22.17	Y	2.41	Y
580	3	3.5	N	-59.55	Y	64.89	Y
581	3.5	2	Y	-8.58	N	-18.76	Y
582	3.5	5	N	-45.13	Y	114.76	Y
583	3.5	3	Y	-16.69	N	8.44	Y
584	3.5	3	N	-4.87	N	4.68	Y
585	2.5	3.5	Y	-39.02	Y	15.35	N
586	5.5	3.5	Y	17.74	Y	-127.15	Y
587	5	3.5	Y	29.89	Y	-62.58	Y
588	4.5	3.5	Y	-2.31	N	48.54	N
589	3.5	1.5	Y	8.83	Y	-38.73	Y
590	4	3.5	N	15.57	Y	38.51	N
591	3.5	1.5	Y	116.34	Y	-100.27	Y
592	3.5	2.5	Y	53.55	Y	-76.28	Y
593	3.5	4	Y	-4.41	Y	96.19	Y
594	3.5	5.5	Y	-101.93	Y	169.88	Y
595	3.5	5	Y	-12.74	Y	140.39	Y
596	3.5	5.5	Y	-45.97	Y	168.86	Y
597	3.5	4	Y	-16.88	Y	23.43	N
598	3.5	4.5	Y	-7.32	Y	56.51	Y
599	5.5	3.5	Y	23.58	Y	-7.76	Y
600	4	3.5	Y	24.45	Y	-24.86	Y
601	1.5	3.5	Y	-90.33	Y	41.44	Y
602	3.5	4.5	Y	-49.61	Y	43.15	Y

603	2	3.5	Y	-111.79	Y	205.92	Y
604	4.5	3.5	Y	13.57	Y	9.32	Y
605	3.5	2	Y	73.91	Y	-24.85	Y
606	2.5	3.5	Y	-28.03	Y	34.85	Y
607	3	3.5	N	-31.00	Y	33.27	Y
608	2	3.5	N	-70.15	Y	87.20	Y

Participant 5, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
609	3.5	1.5	Y	38.74	Y	-44.36	Y
610	3.5	2.5	Y	-4.45	N	28.70	Y
611	1.5	3.5	N	-170.33	Y	162.10	Y
612	4	3.5	Y	65.96	Y	-192.81	Y
613	3.5	2	Y	5.96	Y	24.77	Y
614	3.5	4	N	10.08	N	59.62	N
615	2	3.5	Y	-119.01	Y	56.63	N
616	3.5	2	Y	74.26	Y	38.23	Y
617	4	3.5	Y	-26.78	N	80.63	Y
618	3.5	5	Y	11.22	N	15.11	N
619	3.5	5.5	N	-19.91	Y	161.15	Y
620	5.5	3.5	Y	-27.19	N	54.60	Y
621	5.5	3.5	Y	14.09	Y	86.21	Y
622	4.5	3.5	Y	-71.57	N	184.17	N
623	3.5	5	Y	-22.91	Y	106.93	Y
624	3.5	1.5	Y	47.46	Y	13.41	Y
625	3	3.5	N	36.17	N	-56.84	N
626	3.5	4.5	Y	-11.33	Y	42.61	N
627	2.5	3.5	Y	-77.55	Y	98.49	N
628	5	3.5	Y	23.29	Y	38.06	Y
629	3.5	4	N	-8.20	Y	36.37	N
630	5	3.5	N	9.28	Y	203.85	N
631	3.5	3	N	11.24	Y	255.37	N
632	3.5	5.5	Y	-12.30	Y	360.53	Y
633	3	3.5	N	-0.18	Y	158.55	Y
634	3.5	4.5	N	-126.27	Y	121.63	Y
635	3.5	3	Y	-5.67	N	97.05	Y
636	4.5	3.5	Y	-26.11	N	202.27	N
637	3.5	2.5	Y	42.42	Y	-83.53	Y
638	1.5	3.5	Y	-191.28	Y	325.72	Y
639	2.5	3.5	Y	-107.84	Y	372.12	Y
640	2	3.5	Y	-82.12	Y	314.03	Y

Participant 6, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
641	2.5	3.5	Y	-19.91	Y	199.66	Y
642	3.5	1.5	Y	18.31	Y	58.73	Y
643	3.5	5.5	Y	-2.30	Y	101.61	N
644	5.5	3.5	Y	-0.99	N	31.39	Y

645	4	3.5	Y	6.28	Y	89.47	Y
646	3.5	2.5	Y	-16.35	N	60.73	Y
647	4	3.5	N	-20.51	N	110.74	Y
648	3.5	3	Y	33.18	Y	-4.56	Y
649	4.5	3.5	N	-10.48	N	189.11	N
650	3.5	4.5	N	-11.43	Y	145.52	Y
651	3.5	5	Y	-31.61	Y	128.47	Y
652	3.5	4	Y	-9.18	Y	191.17	Y
653	3.5	2	Y	88.46	Y	-39.87	Y
654	5.5	3.5	Y	-31.45	N	145.49	N
655	3.5	5	Y	-12.34	Y	215.92	Y
656	4.5	3.5	N	21.20	Y	-21.13	Y
657	3	3.5	Y	-52.34	Y	52.96	N
658	3.5	2	Y	71.41	Y	-41.06	Y
659	1.5	3.5	Y	-	-	-	-
660	3.5	4.5	Y	17.96	N	154.69	Y
661	2.5	3.5	Y	-69.03	Y	252.68	Y
662	3.5	1.5	Y	112.11	Y	-80.57	Y
663	2	3.5	Y	-70.70	Y	254.97	Y
664	3.5	5.5	Y	-35.30	Y	157.84	Y
665	5	3.5	Y	0.66	Y	61.85	Y
666	3.5	3	Y	-19.00	N	78.10	Y
667	3.5	2.5	Y	10.50	Y	120.97	N
668	1.5	3.5	Y	-122.95	Y	343.99	Y
669	5	3.5	Y	-11.79	N	97.35	Y
670	3	3.5	Y	-1.47	Y	30.34	N
671	2	3.5	Y	-91.07	Y	184.78	Y
672	3.5	4	Y	-36.22	Y	224.92	Y

Participant 6, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
673	3.5	5.5	Y	-63.00	Y	173.83	Y
674	3.5	4.5	N	-42.97	Y	81.49	Y
675	3	3.5	Y	-56.86	Y	166.19	Y
676	3.5	3	Y	24.37	Y	25.37	Y
677	3.5	1.5	Y	16.79	Y	2.94	Y
678	3	3.5	N	-20.33	Y	62.66	N
679	1.5	3.5	Y	-154.92	Y	265.61	Y
680	3.5	4	Y	-49.31	Y	72.30	N
681	4	3.5	N	22.05	Y	22.06	Y
682	3.5	2.5	Y	-14.78	N	90.06	N
683	2.5	3.5	Y	-78.15	Y	143.57	Y
684	2	3.5	Y	-111.24	Y	223.54	Y
685	2	3.5	Y	-52.86	Y	126.56	Y
686	5.5	3.5	Y	-4.24	N	8.10	Y
687	3.5	4.5	N	-2.93	Y	36.61	N
688	3.5	3	N	-22.72	N	77.34	N
689	3.5	4	Y	-20.87	Y	117.35	Y
690	1.5	3.5	Y	-84.23	Y	153.04	Y
691	4.5	3.5	Y	16.55	Y	30.30	Y
692	3.5	1.5	Y	72.82	Y	-45.69	Y
693	5	3.5	Y	33.82	Y	-15.51	Y
694	3.5	5	Y	-39.10	Y	146.63	Y

695	4	3.5	Y	49.85	Y	-19.90	Y
696	3.5	5	Y	-40.73	Y	105.23	Y
697	3.5	2.5	Y	84.18	Y	-8.27	Y
698	5	3.5	Y	-68.86	N	115.32	N
699	3.5	2	Y	49.26	Y	-7.11	Y
700	2.5	3.5	Y	-60.72	Y	115.49	Y
701	5.5	3.5	Y	2.41	Y	26.31	Y
702	3.5	2	Y	59.01	Y	16.18	Y
703	3.5	5.5	Y	-21.87	Y	138.18	Y
704	4.5	3.5	Y	38.33	Y	0.08	Y

Participant 6, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
705	1.5	3.5	Y	-113.73	Y	245.72	Y
706	3	3.5	N	-3.19	Y	144.20	N
707	3.5	5	Y	-30.70	Y	203.43	Y
708	3.5	4	Y	-19.37	Y	274.40	Y
709	5	3.5	Y	-2.62	N	225.36	N
710	3.5	3	Y	34.26	Y	151.41	Y
711	3.5	2	Y	10.08	Y	98.93	Y
712	3.5	2	Y	31.12	Y	-3.03	Y
713	3.5	4.5	N	52.35	N	0.44	N
714	5.5	3.5	Y	-14.54	N	248.65	N
715	2	3.5	Y	-90.86	Y	291.62	Y
716	3.5	5.5	N	-4.86	Y	162.41	N
717	2.5	3.5	Y	-81.78	Y	272.53	Y
718	4.5	3.5	Y	-23.54	N	238.94	N
719	4	3.5	N	12.93	Y	225.07	N
720	3.5	2.5	Y	6.55	Y	183.49	Y
721	3.5	3	Y	-1.91	N	256.06	N
722	5.5	3.5	Y	46.97	Y	-44.14	Y
723	5	3.5	Y	5.44	Y	274.14	N
724	1.5	3.5	Y	-126.79	Y	533.87	Y
725	4	3.5	N	-10.66	N	168.05	Y
726	3.5	5.5	Y	-51.14	Y	340.99	Y
727	3.5	1.5	Y	30.05	Y	-11.47	Y
728	2.5	3.5	Y	-102.91	Y	309.48	Y
729	3	3.5	Y	-54.82	Y	251.17	Y
730	2	3.5	Y	-11.39	Y	179.98	N
731	3.5	4	Y	-43.18	Y	259.72	Y
732	4.5	3.5	N	-23.74	N	209.82	N
733	3.5	2.5	Y	-28.57	N	139.50	Y
734	3.5	1.5	Y	51.27	Y	108.94	Y
735	3.5	5	N	-15.52	Y	321.67	Y
736	3.5	4.5	Y	-9.01	Y	81.31	N

Participant 6, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct

737	4	3.5	Y	-0.53	N	-0.12	Y
738	5.5	3.5	Y	11.07	Y	6.29	Y
739	3.5	3	N	-3.53	N	75.25	N
740	5	3.5	Y	1.78	Y	-19.36	Y
741	2	3.5	Y	-40.66	Y	68.48	Y
742	2	3.5	Y	-34.13	Y	107.26	Y
743	1.5	3.5	Y	-39.97	Y	70.68	Y
744	3.5	2.5	N	34.87	Y	-12.37	Y
745	3.5	4.5	N	2.07	N	5.61	N
746	3.5	3	N	15.17	Y	-22.16	Y
747	2.5	3.5	Y	-59.88	Y	138.15	Y
748	3.5	4	Y	-13.60	Y	115.13	Y
749	3.5	2	Y	-41.12	N	51.01	N
750	3.5	1.5	Y	132.79	Y	-107.56	Y
751	3.5	5.5	Y	15.70	N	107.61	Y
752	3.5	2.5	Y	29.30	Y	-1.43	Y
753	3.5	5	Y	-3.01	Y	95.57	Y
754	3	3.5	Y	-13.47	Y	63.15	Y
755	4	3.5	N	-6.47	N	36.41	Y
756	1.5	3.5	Y	-56.96	Y	116.75	Y
757	3.5	5.5	Y	-10.21	Y	145.78	Y
758	2.5	3.5	Y	-39.26	Y	115.55	Y
759	3.5	2	Y	20.76	Y	10.70	Y
760	5.5	3.5	Y	15.92	Y	42.98	Y
761	3	3.5	N	0.85	N	19.95	N
762	4.5	3.5	Y	1.34	Y	65.45	N
763	3.5	1.5	Y	4.38	Y	-4.92	Y
764	5	3.5	Y	31.64	Y	-28.72	Y
765	3.5	4.5	Y	-	-	-	-
766	3.5	4	Y	-41.85	Y	99.28	Y
767	3.5	5	N	-2.84	Y	89.76	Y
768	4.5	3.5	Y	12.92	Y	19.16	Y

Participant 7, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
769	2.5	3.5	Y	-	-	-	-
770	2	3.5	Y	-33.01	Y	123.08	Y
771	4.5	3.5	Y	53.89	Y	34.72	N
772	1.5	3.5	Y	-94.78	Y	105.50	Y
773	4	3.5	Y	55.86	Y	-100.05	Y
774	3.5	2.5	Y	77.18	Y	-69.71	Y
775	3.5	2	Y	36.45	Y	-52.57	Y
776	3.5	3	Y	6.94	Y	38.80	N
777	3	3.5	N	-19.26	Y	105.44	Y
778	5	3.5	Y	23.89	Y	-6.83	Y
779	3	3.5	N	-0.66	Y	17.15	N
780	3.5	5	Y	-28.12	Y	145.80	Y
781	3.5	4	Y	-45.68	Y	122.26	Y
782	5.5	3.5	Y	41.93	Y	-47.28	Y
783	4.5	3.5	Y	23.25	Y	-16.64	Y
784	3.5	5	Y	-5.66	Y	20.33	N
785	1.5	3.5	Y	-60.05	Y	196.71	Y
786	3.5	2.5	Y	60.08	Y	-75.81	Y

787	5	3.5	Y	41.86	Y	8.63	Y
788	3.5	4	N	-7.72	Y	67.45	Y
789	2.5	3.5	N	-	-	-	-
790	3.5	5.5	Y	-4.72	Y	32.85	Y
791	3.5	4.5	N	-26.84	Y	-9.98	N
792	2	3.5	Y	-63.94	Y	139.88	Y
793	3.5	1.5	Y	59.60	Y	-22.90	Y
794	4	3.5	Y	-2.30	N	40.05	N
795	3.5	1.5	Y	110.53	Y	-43.83	Y
796	3.5	5.5	Y	-13.91	Y	50.89	Y
797	3.5	2	Y	50.17	Y	-11.92	Y
798	3.5	4.5	Y	-13.04	Y	67.68	Y
799	5.5	3.5	Y	32.62	Y	-41.32	Y
800	3.5	3	Y	41.71	Y	-27.42	Y

Participant 7, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
801	3.5	2.5	Y	31.74	Y	-24.84	Y
802	1.5	3.5	Y	-214.14	Y	288.30	Y
803	3.5	1.5	Y	116.67	Y	-59.48	Y
804	3.5	3	Y	13.54	Y	27.04	Y
805	3.5	1.5	Y	103.42	Y	-107.12	Y
806	3.5	4.5	Y	-34.44	Y	30.64	N
807	5	3.5	Y	0.24	Y	26.68	Y
808	3.5	2	Y	150.87	Y	-95.99	Y
809	5	3.5	Y	9.62	Y	-153.42	Y
810	3.5	2.5	Y	43.90	Y	-40.53	Y
811	3.5	2	Y	7.72	Y	-3.27	Y
812	4	3.5	N	10.34	Y	-15.30	Y
813	4.5	3.5	N	-21.25	N	133.06	N
814	3.5	5.5	Y	-32.34	Y	158.57	Y
815	1.5	3.5	Y	-169.36	Y	268.04	Y
816	2	3.5	Y	-102.78	Y	120.98	Y
817	3.5	5	Y	8.00	N	37.46	N
818	2.5	3.5	Y	-	-	-	-
819	2	3.5	Y	-108.67	Y	157.63	Y
820	3.5	5	N	-13.17	Y	31.53	N
821	3.5	4.5	N	18.43	N	15.95	N
822	3	3.5	Y	-22.29	Y	104.14	Y
823	4	3.5	Y	11.14	Y	-21.37	Y
824	5.5	3.5	Y	11.02	Y	-75.60	Y
825	3	3.5	Y	-79.68	Y	154.96	Y
826	3.5	4	Y	-41.23	Y	112.40	Y
827	4.5	3.5	Y	-10.17	N	61.21	N
828	3.5	4	Y	-50.79	Y	169.91	Y
829	2.5	3.5	Y	-28.57	Y	82.30	Y
830	3.5	3	N	-18.48	N	119.53	N
831	3.5	5.5	Y	-	-	-	-
832	5.5	3.5	Y	-4.57	N	-107.37	Y

Participant 7, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
833	4	3.5	Y	-20.08	N	41.98	Y
834	3.5	4	Y	-31.36	Y	56.73	Y
835	5.5	3.5	Y	30.23	Y	-62.47	Y
836	3.5	2	Y	63.35	Y	-70.64	Y
837	3.5	4.5	Y	-26.87	Y	23.25	N
838	2	3.5	Y	-54.85	Y	102.55	Y
839	4.5	3.5	Y	-47.88	N	68.80	N
840	2.5	3.5	N	-15.91	Y	-16.08	N
841	3.5	4	N	13.85	N	64.05	Y
842	1.5	3.5	Y	-40.00	Y	140.15	Y
843	3.5	3	N	-6.94	N	74.68	N
844	2	3.5	Y	-128.47	Y	152.50	Y
845	3.5	2.5	Y	92.15	Y	-55.12	Y
846	3.5	5.5	Y	-67.91	Y	167.72	Y
847	3.5	2.5	Y	38.39	Y	-23.21	Y
848	5	3.5	Y	33.91	Y	-96.70	Y
849	3.5	5.5	Y	-	-	-	-
850	3.5	1.5	Y	37.27	Y	-62.01	Y
851	3.5	3	Y	-23.15	N	3.06	Y
852	4.5	3.5	Y	-59.37	N	82.85	N
853	1.5	3.5	Y	-166.57	Y	159.84	Y
854	3.5	4.5	N	-24.60	Y	14.64	N
855	5.5	3.5	Y	37.96	Y	30.70	Y
856	3.5	2	Y	28.11	Y	-3.89	Y
857	3	3.5	N	-36.31	Y	21.00	N
858	3	3.5	N	-84.89	Y	137.89	Y
859	2.5	3.5	Y	-88.47	Y	142.09	Y
860	3.5	1.5	Y	94.85	Y	-58.06	Y
861	3.5	5	Y	-75.74	Y	77.89	Y
862	5	3.5	Y	4.32	Y	22.84	Y
863	4	3.5	Y	-26.44	N	29.84	Y
864	3.5	5	Y	-32.35	Y	75.37	Y

Participant 7, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
865	5.5	3.5	N	5.61	Y	-13.06	Y
866	1.5	3.5	Y	-135.11	Y	252.31	Y
867	5	3.5	N	-20.13	N	99.25	N
868	4.5	3.5	Y	-83.78	N	72.47	N
869	3.5	4.5	N	-41.42	Y	62.27	N
870	4	3.5	N	-11.66	N	73.83	N
871	3.5	5	Y	-23.86	Y	132.16	Y
872	5	3.5	Y	1.59	Y	36.94	Y
873	2.5	3.5	Y	-96.07	Y	143.33	Y
874	4	3.5	N	2.71	Y	17.55	Y
875	2	3.5	Y	-75.47	Y	130.97	Y

876	2.5	3.5	Y	-25.64	Y	82.02	Y
877	3.5	2	Y	25.46	Y	-13.46	Y
878	1.5	3.5	Y	-112.52	Y	126.51	Y
879	3.5	4.5	Y	-27.07	Y	43.87	N
880	3.5	5.5	Y	-2.39	Y	28.73	N
881	3.5	4	Y	-62.78	Y	97.51	Y
882	3.5	4	Y	-66.46	Y	148.99	Y
883	3.5	2.5	Y	66.35	Y	-5.49	Y
884	3	3.5	Y	-57.39	Y	104.52	Y
885	3	3.5	N	-91.09	Y	176.93	Y
886	3.5	5.5	Y	-	-	-	-
887	3.5	1.5	Y	144.77	Y	-61.38	Y
888	3.5	3	Y	-32.52	N	137.20	N
889	3.5	1.5	Y	131.42	Y	-73.01	Y
890	3.5	2.5	Y	-3.88	N	18.43	Y
891	2	3.5	Y	-110.49	Y	163.23	Y
892	3.5	2	Y	5.71	Y	-38.63	Y
893	3.5	3	Y	-	-	-	-
894	4.5	3.5	N	-51.60	N	38.07	Y
895	5.5	3.5	Y	6.24	Y	-56.43	Y
896	3.5	5	Y	-41.79	Y	118.98	Y

Participant 8, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
897	3.5	2	Y	126.57	Y	-121.71	Y
898	4	3.5	N	-14.96	N	29.74	Y
899	4.5	3.5	N	-13.22	N	7.48	Y
900	5.5	3.5	Y	19.69	Y	-0.21	Y
901	3.5	3	Y	22.35	Y	114.47	N
902	3.5	5	Y	-3.99	Y	33.09	N
903	3.5	5.5	Y	12.76	N	188.49	Y
904	2.5	3.5	Y	-42.62	Y	103.50	Y
905	4.5	3.5	N	-26.92	N	133.82	N
906	2.5	3.5	Y	-126.47	Y	218.24	Y
907	4	3.5	N	-25.73	N	98.90	N
908	3.5	2	N	80.71	Y	-105.97	Y
909	3.5	1.5	N	3.61	Y	-45.07	Y
910	3.5	4.5	N	-53.13	Y	155.86	Y
911	2	3.5	Y	-135.54	Y	204.06	Y
912	3.5	5.5	Y	-21.37	Y	145.67	Y
913	3.5	4	Y	-69.42	Y	271.52	Y
914	5	3.5	N	-	-	-	-
915	2	3.5	Y	-113.78	Y	257.51	Y
916	5.5	3.5	Y	23.07	Y	-38.24	Y
917	3.5	3	N	-71.65	N	230.19	N
918	3.5	5	Y	-19.04	Y	65.55	N
919	3	3.5	Y	-64.73	Y	114.71	Y
920	3.5	2.5	Y	19.12	Y	-17.33	Y
921	3.5	1.5	Y	65.66	Y	-38.22	Y
922	5	3.5	Y	14.34	Y	29.11	Y
923	3	3.5	Y	-166.49	Y	294.98	Y
924	1.5	3.5	Y	-66.25	Y	169.16	Y
925	3.5	4	Y	-27.08	Y	144.11	Y

926	1.5	3.5	Y	-133.83	Y	303.08	Y
927	3.5	4.5	Y	-6.55	Y	102.88	Y
928	3.5	2.5	Y	48.67	Y	4.39	Y

Participant 8, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
929	3.5	2	Y	26.23	Y	-39.31	Y
930	3	3.5	N	-57.33	Y	46.49	Y
931	5.5	3.5	Y	8.57	Y	-38.15	Y
932	2	3.5	Y	-60.52	Y	33.95	Y
933	3.5	4.5	Y	-56.97	Y	37.74	Y
934	5.5	3.5	Y	20.83	Y	-118.67	Y
935	3.5	1.5	Y	75.67	Y	-95.89	Y
936	3.5	4.5	Y	-40.80	Y	12.02	Y
937	3.5	5.5	Y	-71.42	Y	111.07	Y
938	1.5	3.5	Y	-194.64	Y	107.62	Y
939	3.5	1.5	Y	52.72	Y	-63.89	Y
940	4	3.5	N	-16.65	N	-22.43	Y
941	5	3.5	Y	-5.10	N	-27.16	Y
942	2.5	3.5	Y	-53.68	Y	16.57	Y
943	3.5	5	Y	-41.60	Y	99.08	Y
944	3.5	4	Y	-30.52	Y	58.99	Y
945	3.5	2	Y	13.43	Y	-27.63	Y
946	3.5	2.5	Y	22.66	Y	5.13	Y
947	3.5	3	Y	-3.55	N	-59.05	Y
948	2.5	3.5	Y	-55.29	Y	27.33	Y
949	2	3.5	Y	-68.76	Y	76.74	Y
950	3.5	5	Y	-80.04	Y	118.36	Y
951	4	3.5	N	-16.78	N	-6.81	Y
952	5	3.5	Y	14.06	Y	-55.47	Y
953	1.5	3.5	Y	-137.22	Y	101.61	Y
954	3.5	5.5	Y	-47.22	Y	88.33	Y
955	4.5	3.5	Y	-21.13	N	26.24	N
956	3.5	3	N	-26.34	N	-5.42	Y
957	3.5	4	Y	-38.61	Y	-8.93	N
958	4.5	3.5	N	-33.15	N	32.73	N
959	3.5	2.5	Y	32.87	Y	-86.88	Y
960	3	3.5	Y	-20.84	Y	13.27	Y

Participant 8, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
961	3.5	5.5	Y	-42.71	Y	106.85	Y
962	3.5	1.5	Y	64.44	Y	-60.11	Y
963	4	3.5	N	-60.41	N	136.33	N
964	2.5	3.5	Y	-40.30	Y	84.29	Y
965	5	3.5	N	-19.76	N	5.51	Y
966	5.5	3.5	N	-15.23	N	16.75	Y
967	2	3.5	Y	-70.35	Y	141.47	Y

968	4.5	3.5	N	-44.25	N	102.65	N
969	4	3.5	N	-2.26	N	14.68	Y
970	3	3.5	Y	-49.63	Y	186.20	Y
971	3.5	5.5	Y	-32.24	Y	146.87	Y
972	4.5	3.5	N	-45.70	N	88.62	N
973	3.5	2.5	Y	-5.15	N	11.27	Y
974	3.5	2.5	Y	-13.96	N	-27.88	Y
975	3.5	4.5	N	-42.06	Y	85.19	Y
976	1.5	3.5	Y	-134.37	Y	205.75	Y
977	2	3.5	Y	-74.56	Y	103.31	Y
978	1.5	3.5	Y	-114.09	Y	139.99	Y
979	3.5	3	Y	-31.62	N	12.11	Y
980	3.5	5	Y	-22.96	Y	154.11	Y
981	3.5	4.5	N	11.82	N	25.72	N
982	5.5	3.5	Y	-25.30	N	74.92	Y
983	3.5	2	Y	34.95	Y	4.30	Y
984	5	3.5	Y	5.90	Y	2.63	Y
985	3.5	5	Y	-25.51	Y	67.97	N
986	3	3.5	Y	-46.41	Y	228.27	Y
987	3.5	4	Y	-18.81	Y	103.71	Y
988	3.5	1.5	Y	91.18	Y	-109.05	Y
989	2.5	3.5	Y	-94.18	Y	180.62	Y
990	3.5	4	Y	-32.94	Y	165.85	Y
991	3.5	2	Y	32.95	Y	-30.10	Y
992	3.5	3	Y	-12.99	N	82.54	N

Participant 8, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
993	3.5	2	Y	50.68	Y	-86.10	Y
994	3.5	2.5	Y	110.75	Y	-175.46	Y
995	3.5	2	Y	133.76	Y	-175.00	Y
996	3.5	1.5	Y	54.77	Y	-88.88	Y
997	5	3.5	Y	12.96	Y	-59.19	Y
998	3.5	4	Y	-69.19	Y	16.98	N
999	3.5	4.5	N	-5.64	Y	-13.97	N
1000	3.5	5	Y	-20.82	Y	32.61	Y
1001	3.5	5.5	Y	-48.93	Y	178.93	Y
1002	2	3.5	Y	-68.89	Y	90.66	Y
1003	3.5	5	Y	-63.36	Y	93.19	Y
1004	5.5	3.5	Y	11.50	Y	-41.17	Y
1005	4	3.5	N	-18.15	N	12.32	Y
1006	3.5	2.5	Y	134.01	Y	-107.87	Y
1007	3.5	1.5	Y	94.11	Y	-127.65	Y
1008	2.5	3.5	Y	-97.50	Y	123.37	Y
1009	3.5	4	Y	-24.00	Y	69.78	Y
1010	3.5	3	Y	-96.32	N	165.96	N
1011	2	3.5	Y	-98.43	Y	91.50	Y
1012	3.5	4.5	Y	-61.61	Y	23.99	N
1013	3	3.5	Y	-95.20	Y	60.10	Y
1014	5	3.5	Y	3.36	Y	-32.37	Y
1015	4.5	3.5	N	-47.08	N	121.35	N
1016	3.5	3	Y	27.26	Y	-21.81	Y
1017	1.5	3.5	Y	-54.14	Y	82.05	Y

1018	3.5	5.5	Y	-72.42	Y	148.11	Y
1019	4.5	3.5	Y	11.96	Y	-21.18	Y
1020	1.5	3.5	Y	-143.79	Y	228.10	Y
1021	3	3.5	Y	-14.06	Y	61.34	Y
1022	4	3.5	N	-6.41	N	54.61	N
1023	2.5	3.5	Y	-136.40	Y	151.12	Y
1024	5.5	3.5	Y	17.97	Y	-77.10	Y

Participant 9, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1025	3.5	2	Y	26.56	Y	-19.88	Y
1026	3.5	2.5	N	4.07	Y	-30.31	Y
1027	4	3.5	N	19.76	Y	29.85	Y
1028	3.5	1.5	Y	50.54	Y	-75.05	Y
1029	3.5	5	Y	-36.19	Y	145.70	Y
1030	3.5	4	Y	3.68	N	15.03	N
1031	5.5	3.5	Y	28.44	Y	-109.88	Y
1032	4.5	3.5	N	-30.77	N	63.24	N
1033	3.5	4	Y	-31.21	Y	96.11	Y
1034	3.5	4.5	Y	-52.80	Y	89.78	Y
1035	2.5	3.5	Y	-61.10	Y	87.68	Y
1036	2.5	3.5	Y	-61.58	Y	81.57	Y
1038	3	3.5	Y	-0.47	Y	10.29	N
1039	3.5	2	Y	-6.84	N	-10.95	Y
1040	3	3.5	Y	-17.95	Y	64.62	Y
1041	5	3.5	Y	6.87	Y	-21.19	Y
1042	3.5	5.5	Y	-44.58	Y	129.25	Y
1043	5	3.5	Y	-	-	-	-
1044	2	3.5	Y	-77.21	Y	136.49	Y
1045	3.5	4.5	Y	-29.95	Y	51.80	Y
1046	3	3.5	N	-43.91	Y	29.57	N
1047	5.5	3.5	Y	7.63	Y	-38.94	Y
1048	3.5	2.5	Y	24.54	Y	2.94	Y
1049	4	3.5	N	-17.68	N	22.66	Y
1050	4.5	3.5	Y	6.36	Y	3.52	Y
1051	3.5	5.5	Y	-61.57	Y	132.58	Y
1052	3.5	3	Y	-17.78	N	15.16	Y
1053	1.5	3.5	Y	-135.05	Y	133.48	Y
1054	3.5	1.5	Y	60.78	Y	-95.82	Y
1055	1.5	3.5	Y	-61.74	Y	65.91	Y
1056	3.5	5	Y	-24.12	Y	80.42	Y
1057	2	3.5	Y	-50.19	Y	120.02	Y

Participant 9, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1058	3.5	3	N	-33.94	N	81.33	Y
1059	3.5	4.5	Y	-17.91	Y	-0.35	N
1060	3.5	1.5	Y	4.95	Y	10.18	Y

1061	4	3.5	Y	-1.82	N	53.28	Y
1062	3	3.5	Y	-24.71	Y	111.04	Y
1063	3.5	5.5	N	6.30	N	-10.78	N
1064	3.5	5	N	-9.00	Y	114.07	Y
1065	3.5	4.5	N	38.89	N	55.73	N
1066	1.5	3.5	Y	-74.84	Y	176.90	Y
1067	5.5	3.5	Y	-11.72	N	58.36	Y
1068	3.5	2.5	Y	-4.66	N	24.65	Y
1069	2	3.5	Y	-71.24	Y	251.86	Y
1070	3.5	4	N	-6.66	Y	166.71	Y
1071	3.5	2.5	Y	126.22	Y	-64.39	Y
1072	4	3.5	Y	-5.69	N	48.81	Y
1073	4.5	3.5	N	-14.93	N	114.61	N
1074	5	3.5	Y	-65.11	N	146.33	N
1075	2.5	3.5	Y	-1.74	Y	74.48	N
1076	3.5	2	Y	15.36	Y	-59.92	Y
1077	1.5	3.5	Y	-80.89	Y	282.79	Y
1078	3	3.5	N	-46.44	Y	128.11	Y
1079	2.5	3.5	Y	-83.19	Y	119.25	Y
1080	5.5	3.5	Y	-34.30	N	145.61	N
1081	3.5	1.5	Y	7.23	Y	-44.42	Y
1082	3.5	5	Y	-	-	-	-
1083	3.5	5.5	Y	-33.43	Y	151.49	Y
1084	2	3.5	Y	-98.79	Y	202.60	Y
1085	3.5	3	N	-81.85	N	183.54	N
1086	5	3.5	Y	-28.82	N	94.03	N
1087	3.5	4	N	-	-	-	-
1088	4.5	3.5	Y	-	-	-	-
1089	3.5	2	Y	8.75	Y	-0.64	Y

Participant 9, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1090	2	3.5	Y	-57.76	Y	100.29	Y
1091	1.5	3.5	Y	-169.27	Y	226.75	Y
1092	3.5	4	Y	-63.08	Y	102.64	Y
1093	3.5	2	Y	105.31	Y	-104.99	Y
1094	3.5	5.5	Y	-58.58	Y	189.57	Y
1095	2.5	3.5	Y	-108.16	Y	150.94	Y
1096	3.5	2.5	N	-9.00	N	14.26	Y
1097	3.5	1.5	Y	118.35	Y	-94.78	Y
1098	3.5	4.5	Y	-10.61	Y	85.97	Y
1099	3.5	3	N	-1.03	N	23.03	Y
1100	4.5	3.5	Y	-13.13	N	157.06	N
1101	3.5	4	Y	-31.10	Y	158.94	Y
1102	3.5	4.5	Y	-50.93	Y	136.69	Y
1103	4	3.5	Y	31.77	Y	-49.40	Y
1104	3.5	5	Y	-60.56	Y	162.21	Y
1105	4	3.5	Y	15.92	Y	28.08	Y
1106	5	3.5	Y	21.20	Y	-55.81	Y
1107	2.5	3.5	Y	-75.36	Y	106.89	Y
1108	4.5	3.5	Y	8.65	Y	54.62	Y
1109	5.5	3.5	Y	9.08	Y	-10.73	Y
1110	1.5	3.5	Y	-53.38	Y	156.71	Y

1111	3.5	2	Y	35.51	Y	-10.83	Y
1112	5.5	3.5	Y	15.68	Y	22.65	Y
1113	2	3.5	Y	-82.54	Y	151.23	Y
1114	5	3.5	Y	26.63	Y	-83.03	Y
1115	3.5	3	N	-3.97	N	55.19	Y
1116	3.5	1.5	Y	19.42	Y	14.28	Y
1117	3	3.5	N	-32.22	Y	106.52	Y
1118	3.5	5.5	Y	-32.31	Y	212.44	Y
1119	3	3.5	Y	-38.33	Y	90.12	Y
1120	3.5	2.5	Y	64.49	Y	-25.36	Y
1121	3.5	5	Y	-39.00	Y	186.72	Y

Participant 9, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1122	3	3.5	Y	-	-	-	-
1123	3.5	2	Y	17.89	Y	-2.33	Y
1124	3.5	4	Y	-11.68	Y	141.84	Y
1125	3.5	3	Y	39.01	Y	39.31	Y
1126	2	3.5	Y	-98.05	Y	286.05	Y
1127	1.5	3.5	Y	-136.91	Y	326.43	Y
1128	4.5	3.5	Y	24.70	Y	135.76	N
1129	3.5	1.5	Y	100.94	Y	-75.25	Y
1130	5	3.5	N	-	-	-	-
1131	1.5	3.5	Y	-112.84	Y	315.28	Y
1132	5	3.5	Y	30.72	Y	73.20	Y
1133	3.5	5	Y	-0.06	Y	122.93	Y
1134	3.5	2	Y	61.90	Y	-7.41	Y
1135	5.5	3.5	Y	32.05	Y	-41.82	Y
1136	4	3.5	N	-9.21	N	187.35	N
1137	3.5	1.5	Y	126.39	Y	-28.11	Y
1138	3.5	5	Y	34.66	N	5.76	N
1139	2	3.5	Y	-13.89	Y	209.47	Y
1140	3	3.5	Y	-	-	-	-
1141	5.5	3.5	Y	23.24	Y	-41.51	Y
1142	4.5	3.5	N	-	-	-	-
1143	3.5	4	N	-12.71	Y	127.43	Y
1144	3.5	4.5	N	19.92	N	-38.55	N
1145	3.5	3	Y	52.30	Y	-11.59	Y
1146	3.5	2.5	Y	-5.85	N	84.26	Y
1147	2.5	3.5	Y	-31.96	Y	235.05	Y
1148	3.5	5.5	Y	-28.67	Y	223.09	Y
1149	3.5	2.5	Y	-	-	-	-
1150	3.5	4.5	N	-15.21	Y	51.70	N
1151	2.5	3.5	Y	-88.95	Y	238.95	Y
1152	4	3.5	Y	-20.97	N	94.91	Y
1153	3.5	5.5	Y	-35.81	Y	184.85	Y

Participant 10, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1154	3.5	4.5	N	-	-	-	-
1155	3.5	3	Y	27.51	Y	-40.41	Y
1156	5	3.5	Y	-	-	-	-
1157	3	3.5	Y	-86.75	Y	154.63	Y
1158	3.5	1.5	Y	93.53	Y	22.79	Y
1159	3.5	5.5	Y	-72.40	Y	219.45	Y
1160	4.5	3.5	Y	-	-	-	-
1161	2	3.5	Y	-98.85	Y	207.22	Y
1162	3.5	2	Y	84.41	Y	-43.17	Y
1163	3.5	4	Y	-82.18	Y	311.58	Y
1164	4	3.5	Y	-33.76	N	226.77	N
1165	1.5	3.5	Y	-100.32	Y	321.91	Y
1166	3	3.5	N	-60.17	Y	154.85	Y
1167	4.5	3.5	Y	62.23	Y	-132.15	Y
1168	5	3.5	Y	-5.99	N	14.33	Y
1169	3.5	5.5	N	3.88	N	203.15	Y
1170	3.5	3	Y	-26.29	N	141.86	N
1171	3.5	4	Y	-72.12	Y	173.09	Y
1172	3.5	2	Y	59.15	Y	-69.18	Y
1173	3.5	5	N	-14.71	Y	20.58	N
1174	3.5	1.5	Y	61.42	Y	-20.88	Y
1175	5.5	3.5	Y	-6.08	N	-55.99	Y
1176	3.5	5	Y	-63.96	Y	257.62	Y
1177	5.5	3.5	Y	100.21	Y	-151.60	Y
1178	1.5	3.5	Y	-124.26	Y	231.68	Y
1179	2.5	3.5	Y	-	-	-	-
1180	2	3.5	N	-53.20	Y	58.67	N
1181	3.5	2.5	Y	47.41	Y	-68.26	Y
1182	4	3.5	Y	-35.90	N	91.20	N
1183	3.5	4.5	N	-44.20	Y	83.66	N
1184	2.5	3.5	Y	-115.90	Y	202.37	Y
1185	3.5	2.5	Y	71.52	Y	-112.26	Y

Participant 10, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1186	3.5	4	Y	-1.99	Y	14.17	N
1187	3.5	4	Y	-31.21	Y	23.02	N
1188	3	3.5	Y	-	-	-	-
1189	1.5	3.5	Y	-103.56	Y	57.00	Y
1190	2.5	3.5	N	-31.12	Y	34.68	Y
1191	3.5	3	N	-71.41	N	56.47	N
1192	3.5	5.5	Y	-54.71	Y	43.33	Y
1193	1.5	3.5	Y	-93.46	Y	55.11	Y
1194	2	3.5	Y	-59.53	Y	40.13	Y
1195	5.5	3.5	Y	26.11	Y	-11.88	Y
1196	3.5	2.5	Y	-3.73	N	-1.70	Y
1197	3.5	4.5	Y	-9.84	Y	-8.61	N

1198	4	3.5	Y	19.19	Y	11.25	Y
1199	3.5	3	Y	43.08	Y	11.11	Y
1200	5	3.5	Y	-	-	-	-
1201	3.5	2	Y	92.55	Y	-61.17	Y
1202	5.5	3.5	Y	28.75	Y	-12.18	Y
1203	3.5	2.5	Y	59.28	Y	-28.73	Y
1204	2.5	3.5	Y	-	-	-	-
1205	4.5	3.5	Y	5.16	Y	30.00	N
1206	3.5	4.5	N	-31.09	Y	-5.92	N
1207	3.5	5	Y	-89.35	Y	156.53	Y
1208	3.5	1.5	Y	105.20	Y	-78.27	Y
1209	3.5	5.5	Y	-48.64	Y	60.78	Y
1210	2	3.5	Y	-127.91	Y	154.74	Y
1211	3.5	1.5	Y	56.04	Y	-64.73	Y
1212	5	3.5	Y	13.80	Y	-47.32	Y
1213	4.5	3.5	Y	-10.27	N	131.59	N
1214	4	3.5	Y	5.93	Y	58.88	N
1215	3.5	2	Y	109.82	Y	-78.96	Y
1216	3	3.5	Y	-77.30	Y	132.45	Y
1217	3.5	5	Y	-3.21	Y	44.72	Y

Participant 10, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change $[m/s^2]$	Peak Amplitude Correct
1218	3.5	5.5	Y	-53.37	Y	405.64	Y
1219	1.5	3.5	Y	-154.94	Y	353.31	Y
1220	3.5	4.5	Y	-48.08	Y	277.28	Y
1221	5.5	3.5	Y	36.22	Y	-83.16	Y
1222	3.5	1.5	N	69.20	Y	-55.21	Y
1223	3.5	5.5	N	-29.32	Y	81.97	N
1224	2.5	3.5	Y	4.98	N	99.23	Y
1225	3.5	5	N	-58.94	Y	255.54	Y
1226	3.5	3	N	7.94	Y	90.53	N
1227	1.5	3.5	Y	-153.64	Y	291.83	Y
1228	3.5	2	Y	151.52	Y	-212.35	Y
1229	2	3.5	Y	-152.00	Y	264.72	Y
1230	4	3.5	N	-23.11	N	74.23	Y
1231	3.5	4	Y	-33.68	Y	229.62	Y
1232	5.5	3.5	Y	-16.32	N	31.12	Y
1233	2.5	3.5	Y	-117.70	Y	261.22	Y
1234	5	3.5	Y	-11.84	N	-21.47	Y
1235	3.5	2.5	Y	32.38	Y	-72.95	Y
1236	3.5	5	Y	-9.85	Y	126.34	Y
1237	3.5	4.5	N	-11.31	Y	-13.99	N
1238	3.5	2.5	Y	78.59	Y	4.73	Y
1239	2	3.5	Y	-113.62	Y	214.86	Y
1240	4.5	3.5	Y	-3.90	N	10.07	Y
1241	3.5	3	Y	89.74	Y	-40.21	Y
1242	3	3.5	Y	-52.12	Y	102.01	Y
1243	3.5	4	Y	-102.59	Y	156.65	Y
1244	3	3.5	N	-42.71	Y	16.44	N
1245	4.5	3.5	N	-82.71	N	167.66	N
1246	3.5	2	Y	89.34	Y	-91.47	Y
1247	3.5	1.5	Y	81.39	Y	-124.13	Y

1248	4	3.5	Y	13.49	Y	-32.31	Y
1249	5	3.5	N	-7.74	N	39.62	Y

Participant 10, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1250	3.5	5	Y	-16.30	Y	81.93	Y
1251	2	3.5	Y	-85.47	Y	110.02	Y
1252	3.5	4	Y	-72.42	Y	112.75	Y
1253	5	3.5	Y	0.14	Y	-72.29	Y
1254	3.5	2.5	Y	-20.52	N	-41.96	Y
1255	3.5	2.5	N	4.83	Y	14.82	Y
1256	2	3.5	Y	-58.53	Y	106.19	Y
1257	2.5	3.5	N	-79.19	Y	90.10	Y
1258	5.5	3.5	Y	-35.40	N	79.66	N
1259	3.5	1.5	Y	61.91	Y	-38.82	Y
1260	3.5	5	Y	-104.21	Y	125.90	Y
1261	3.5	4.5	Y	-44.27	Y	23.27	Y
1262	5	3.5	Y	9.99	Y	-97.79	Y
1263	3.5	4	Y	-52.84	Y	5.14	N
1264	2.5	3.5	Y	-75.20	Y	121.58	Y
1265	3.5	5.5	Y	-69.24	Y	120.96	Y
1266	3.5	2	Y	72.75	Y	-115.62	Y
1267	4.5	3.5	Y	-6.54	N	-40.06	Y
1268	3.5	3	Y	-54.84	N	32.76	N
1269	3	3.5	N	-48.20	Y	8.12	N
1270	3.5	3	Y	27.72	Y	-73.53	Y
1271	4.5	3.5	Y	4.39	Y	-78.73	Y
1272	4	3.5	Y	-9.87	N	-14.47	Y
1273	5.5	3.5	Y	13.60	Y	-149.23	Y
1274	1.5	3.5	Y	-96.30	Y	200.21	Y
1275	3.5	1.5	Y	67.30	Y	-84.57	Y
1276	4	3.5	N	-0.30	N	-4.99	Y
1277	3.5	4.5	Y	-26.67	Y	82.50	Y
1278	3	3.5	Y	-17.43	Y	37.95	Y
1279	1.5	3.5	Y	-113.86	Y	107.00	Y
1280	3.5	2	Y	15.14	Y	-22.28	Y
1281	3.5	5.5	Y	-61.02	Y	104.88	Y

Participant 11, Flexible Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1282	1.5	3.5	N	-112.06	Y	176.74	Y
1283	2.5	3.5	Y	-56.02	Y	279.32	Y
1284	3.5	3	Y	18.32	Y	41.88	Y
1285	4.5	3.5	N	-0.30	N	58.96	Y
1286	5	3.5	Y	-2.95	N	29.05	Y
1287	5	3.5	Y	5.72	Y	62.23	Y
1288	1.5	3.5	Y	-94.62	Y	228.25	Y
1289	4	3.5	Y	-6.84	N	2.31	Y

1290	3.5	2.5	Y	89.47	Y	-38.48	Y
1291	3.5	4.5	N	15.08	N	11.08	N
1292	3.5	1.5	Y	67.11	Y	-28.69	Y
1293	3.5	4.5	N	6.53	N	47.33	N
1294	3.5	2.5	Y	-7.37	N	68.69	Y
1295	4.5	3.5	Y	13.46	Y	88.13	N
1296	3.5	3	N	-11.59	N	127.45	N
1297	3.5	5	Y	-24.30	Y	109.15	Y
1298	3.5	1.5	Y	48.67	Y	1.59	Y
1299	5.5	3.5	Y	17.80	Y	79.74	N
1300	3.5	2	Y	81.73	Y	-75.25	Y
1301	5.5	3.5	Y	48.71	Y	-73.74	Y
1302	3	3.5	N	-5.98	Y	84.17	Y
1303	2	3.5	Y	-36.99	Y	189.96	Y
1304	3.5	2	Y	138.38	Y	-116.24	Y
1305	3.5	5.5	Y	-7.25	Y	164.54	Y
1306	3.5	4	Y	-	-	-	-
1307	2	3.5	Y	-59.59	Y	117.96	Y
1308	2.5	3.5	Y	-55.92	Y	233.78	Y
1309	3.5	5	N	6.13	N	176.27	Y
1310	3	3.5	Y	14.83	N	74.81	N
1311	3.5	5.5	Y	-45.67	Y	147.97	Y
1312	3.5	4	N	16.43	N	41.67	N
1313	4	3.5	Y	5.52	Y	119.05	N

Participant 11, Flexible High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1314	1.5	3.5	Y	-64.77	Y	303.42	Y
1315	5	3.5	Y	-	-	-	-
1316	3	3.5	N	25.23	N	-42.35	N
1317	3.5	2	Y	30.65	Y	45.14	Y
1318	2	3.5	Y	-82.28	Y	345.30	Y
1319	4.5	3.5	Y	-28.84	N	148.14	N
1320	3.5	4.5	N	3.18	N	111.09	N
1321	3.5	4.5	Y	-16.92	Y	131.86	N
1322	5.5	3.5	Y	37.36	Y	95.37	Y
1323	3.5	5	Y	-14.98	Y	100.22	N
1324	5.5	3.5	Y	-6.15	N	59.29	Y
1325	1.5	3.5	Y	-35.70	Y	333.03	Y
1326	3.5	5.5	Y	-69.15	Y	347.32	Y
1327	3.5	3	Y	-12.74	N	310.35	N
1328	3	3.5	Y	-63.77	Y	355.57	Y
1329	3.5	5	Y	-3.50	Y	130.36	N
1330	5	3.5	Y	32.74	Y	4.97	Y
1331	4.5	3.5	Y	-25.30	N	156.70	N
1332	3.5	4	N	-	-	-	-
1333	3.5	1.5	Y	94.72	Y	-143.88	Y
1334	3.5	2.5	Y	66.33	Y	-48.77	Y
1335	3.5	5.5	Y	-40.71	Y	302.16	Y
1336	2	3.5	Y	-64.21	Y	250.71	Y
1337	4	3.5	N	-	-	-	-
1338	2.5	3.5	Y	-53.54	Y	291.15	Y
1339	4	3.5	N	-28.21	N	206.99	N

1340	3.5	3	Y	32.64	Y	-22.95	Y
1341	3.5	4	Y	-	-	-	-
1342	3.5	2.5	Y	-	-	-	-
1343	3.5	2	N	45.80	Y	-34.14	Y
1344	2.5	3.5	N	-13.92	Y	110.82	N
1345	3.5	1.5	Y	-63.63	N	173.47	N

Participant 11, Rigid Low Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1346	4.5	3.5	Y	-0.32	N	53.41	N
1347	3.5	5.5	Y	-46.94	Y	81.71	Y
1348	3.5	5	Y	-13.77	Y	52.55	Y
1349	5.5	3.5	Y	16.58	Y	-12.90	Y
1350	4.5	3.5	N	19.01	Y	5.81	Y
1351	3.5	2	Y	34.60	Y	-37.62	Y
1352	1.5	3.5	Y	-48.99	Y	62.44	Y
1353	2.5	3.5	Y	-35.47	Y	80.97	Y
1354	3.5	3	Y	31.46	Y	-51.49	Y
1355	3.5	2.5	Y	-	-	-	-
1356	4	3.5	Y	-14.55	N	52.63	N
1357	1.5	3.5	Y	-72.82	Y	54.91	Y
1358	3.5	5.5	Y	-6.83	Y	80.08	Y
1359	3.5	2	Y	86.03	Y	-24.49	Y
1360	2	3.5	Y	-93.05	Y	161.02	Y
1361	3.5	2.5	Y	38.35	Y	-44.37	Y
1362	2	3.5	Y	-45.85	Y	76.72	Y
1363	3.5	4	Y	9.67	N	-0.33	N
1364	3.5	4.5	Y	19.11	N	-16.52	N
1365	5	3.5	Y	26.06	Y	-15.25	Y
1366	5	3.5	Y	-33.61	N	101.27	N
1367	4	3.5	N	10.34	Y	4.46	Y
1368	5.5	3.5	Y	-3.71	N	49.37	N
1369	3.5	4.5	Y	-32.45	Y	60.37	Y
1370	3	3.5	Y	-9.00	Y	79.64	Y
1371	3.5	1.5	Y	121.28	Y	-81.93	Y
1372	3	3.5	N	-48.21	Y	52.26	Y
1373	3.5	1.5	Y	58.43	Y	-36.49	Y
1374	3.5	4	Y	-21.38	Y	32.44	Y
1375	2.5	3.5	Y	-35.78	Y	87.01	Y
1376	3.5	3	N	55.24	Y	-19.46	Y
1377	3.5	5	Y	-	-	-	-

Participant 11, Rigid High Speed Condition

Unique Sample Number	Left Plate [mm]	Right Plate [mm]	Participant Correct	Peak Frequency Change [Hz]	Peak Frequency Correct	Peak Amplitude Change [m/s^2]	Peak Amplitude Correct
1378	2.5	3.5	Y	-87.91	Y	188.82	Y
1379	3.5	5	Y	-23.78	Y	139.52	Y
1380	5.5	3.5	Y	29.30	Y	-31.53	Y
1381	2.5	3.5	Y	-32.14	Y	192.02	Y

1382	3.5	4	N	-12.88	Y	118.17	Y
1383	3.5	5.5	Y	-27.68	Y	148.37	Y
1384	5	3.5	Y	28.12	Y	0.71	Y
1385	3.5	2.5	Y	-20.26	N	56.42	Y
1386	3.5	5	Y	-	-	-	-
1387	1.5	3.5	Y	-80.57	Y	185.81	Y
1388	4.5	3.5	Y	11.69	Y	61.70	Y
1389	3.5	4.5	Y	-7.07	Y	68.38	N
1390	3.5	2	Y	37.82	Y	-51.63	Y
1391	4	3.5	Y	-	-	-	-
1392	5	3.5	Y	-5.53	N	83.77	Y
1393	5.5	3.5	Y	-24.63	N	58.05	Y
1394	2	3.5	Y	-34.22	Y	264.44	Y
1395	3.5	3	Y	33.98	Y	123.20	N
1396	3.5	3	Y	26.92	Y	15.69	Y
1397	3.5	1.5	Y	29.62	Y	-22.01	Y
1398	3.5	1.5	Y	74.34	Y	-24.23	Y
1399	4.5	3.5	Y	-25.89	N	62.09	Y
1400	2	3.5	Y	-73.08	Y	143.93	Y
1401	3.5	5.5	Y	-52.40	Y	309.49	Y
1402	3.5	2	Y	33.64	Y	-64.11	Y
1403	1.5	3.5	Y	-72.33	Y	178.87	Y
1404	3	3.5	N	-1.30	Y	82.48	N
1405	3.5	4.5	N	23.02	N	0.80	N
1406	3.5	2.5	Y	25.19	Y	-13.49	Y
1407	4	3.5	Y	21.48	Y	75.54	Y
1408	3.5	4	Y	-67.29	Y	313.34	Y
1409	3	3.5	Y	-19.88	Y	177.43	Y

Appendix C

HSIRB Approval Document

WESTERN MICHIGAN UNIVERSITY

Human Subjects Institutional Review Board

Date: November 21, 2016

To: Dae Kim, Principal Investigator
Robert Wall Emerson, Co-Principal Investigator
Koorosh Naghshineh, Co-Principal Investigator

From: Amy Naugle, Ph.D., Chair

Re: HSIRB Project Number 16-11-08

This letter will serve as confirmation that your research project titled "Better Long Cane Design and Biomechanics" has been **approved** under the **expedited** category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note: This research may **only** be conducted exactly in the form it was approved. You must seek specific board approval for any changes in this project (e.g., ***you must request a post approval change to enroll subjects beyond the number stated in your application under "Number of subjects you want to complete the study***)." Failure to obtain approval for changes will result in a protocol deviation. In addition, if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

Reapproval of the project is required if it extends beyond the termination date stated below.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: **November 21, 2017**

1903 W. Michigan Ave., Kalamazoo, MI 49008-5456
PHONE: (269) 387-8293 FAX: (269) 387-8276
CAMPUS SITE: 251 W. Walwood Hall

Informed Consent Document
Western Michigan University

Principal Investigator: Dr. Dae Kim
Co-Principal Investigator: Dr. Robert Wall Emerson
Co-Principal Investigator: Dr. Koorosh Naghshineh
Title of Study: Better Long Cane Design and Biomechanics

You have been invited to the consenting procedure for the research project titled *Better Long Cane Design and Biomechanics* to learn more about the study. This consent document will explain the purpose of this research project and will go over all of the time commitments, the procedures used in the study, and the risks and benefits of participating in this research project. Please read this consent form carefully and completely and please ask any questions if you need more clarification.

What are we trying to find out in this study?
The purpose of the study is to find out whether biomechanical factors such as cane techniques and ergonomic factors such as type of cane tip affect cane user's ability to detect drop-offs, obstacles, or surface texture changes.

Who can participate in this study?
Sighted or legally blind adults with no other disabilities are eligible to participate in the study. Another eligibility criterion includes at least one month of cane training as well as familiarity with both the two-point touch and constant contact techniques.

Where will this study take place?
The study will be conducted at Western Michigan University's College of Engineering and Applied Sciences building or on the sidewalks around the College of Health and Human Services building or the Sangren Hall.

What is the time commitment for participating in this study?
If you choose to participate, you will be asked to attend one 1½ to 2½ hour study session.

What will you be asked to do if you choose to participate in this study?
At the beginning of the session, you will be familiarized with the experiment procedure through verbal briefing and practice trials. Then, at a signal from the experimenter, you will be asked to do one of the following: 1) walk on a sidewalk leading to a prominent curb, 2) walk on a sidewalk on which obstacles (such as construction cones and toys) are placed, or 3) walk on a sidewalk leading to detectable warning tiles. Upon detecting the drop-off, obstacle, or the detectable warning tile, you will stop immediately and say "drop-off", "obstacle" or "DW." If you are participating in a lab study (rather than a real-world setting study), you will be asked to tell which of the two presented aluminum plates feel rougher by swiping the two plates with the long cane.

A certified Orientation and Mobility specialist will be with you at all times to prevent you from stumbling or tripping. If you are sighted, you will be asked to do these tasks without using your vision. You will be asked to complete up to 36 drop-off/obstacle/DW detection trials or up to 128 aluminum plate roughness discrimination trials.

What information is being measured during the study?
We will measure how well you detect drop-offs, obstacles, or surface texture changes with different canes or cane tips using different cane techniques. We will also collect information on magnitude of applied forces and vibration characteristics captured by accelerometers attached to the cane in selected trials.

What are the risks of participating in this study and how will these risks be minimized?
As in all research, there may be unforeseen risks of participating in this study. If an accidental injury occurs, appropriate emergency measures will be taken. If you are participating in an obstacle detection study, one potential risk of participating in this research is the risk of falling by tripping over the presented obstacles. To minimize the risk of such falling, an experienced certified orientation and mobility specialist (one of the experimenters) will walk along the obstacle course next to you to help you stumble. Similarly, if you are participating in a drop-off detection study, to minimize a potential risk for you to stumble off the curb, a certified orientation and mobility specialist (experimenter) will walk next to you to intervene if you fail to detect the drop-off with the cane and continue moving toward the edge of the drop-off. If you are participating in a walking-surface texture change detection study (real-world setting), there is a potential risk that you walk into the street by failing to detect the warning dome tiles installed on the ramp. To minimize such risk, a certified orientation and mobility specialist will walk next to you and stop you if you fail to detect the warning tiles with the cane and continue moving toward the edge of the ramp.

In drop-off and walking-surface texture change detection studies, although remote, there is a potential risk of pedestrian-vehicle conflict in case you stumble off the curb or walk into the street while there is a moving vehicle in the parking lot. To minimize such risk, a sidewalk leading to a quiet parking lot with virtually no traffic at the time of test will be selected for our studies.

Furthermore, to reduce possible fatigue from walking and standing during the trials, you will be provided breaks every twenty minutes. In addition, researchers will frequently check verbally with you to assess your fatigue level. Additional breaks will be provided, if necessary, based on such assessment or upon request from you.

What are the benefits of participating in this study?
There probably are no direct and immediate benefits of participating in this study. However, you may increase their understanding of how different ergonomic and biomechanical factors affect their ability to detect drop-offs, obstacles, and walking-surface texture changes, which is a critical component of safe travel by blind pedestrians. Such understanding may help O&M specialists develop effective strategies for teaching cane techniques.

Are there any costs associated with participating in this study?
There is no cost that will be incurred by you.

Is there any compensation for participating in this study?
You will be paid $40-80 ($40 if the study you participate in requires one primary experiment, which takes approximately 1½ hours, and $80 if the study you participate in requires two primary experiments, which takes approximately 2½ hours) for your participation regardless of whether you complete the study or not. Transportation expenses to and from the study site, if necessary, will be paid by the researcher.

Who will have access to the information collected during this study?
All of the information collected from you is confidential. That means that your name will not appear on any papers on which this information is recorded. The forms will all be coded, and the principal investigator will keep a separate master list with the names of participants and the corresponding code numbers. Once the data are collected and analyzed, the master list will be destroyed.

What if you want to stop participating in this study?
You can choose to stop participating in the study at anytime for any reason. You will not suffer any prejudice or penalty by your decision to stop your participation. You will experience NO consequences either academically or personally if you choose to withdraw from this study.

The investigator can also decide to stop your participation in the study without your consent.

Should you have any questions prior to or during the study, you can contact Dae Kim at 269-387-3447 (dae.kim@wmich.edu) or Dr. Wall Emerson at 269-387-3072 (robert.wall@wmich.edu). You may also contact the Chair, Human Subjects Institutional Review Board at 269-387-8293 or the Vice President for Research at 269-387-8298 if questions arise during the course of the study.

Western Michigan University
H.S.I.R.B.
Approved for use for one year from this date:

NOV 21 2016

x [signature]
HSIRB Office

This consent document has been approved for use for one year by the Human Subjects Institutional Review Board (HSIRB) as indicated by the stamped date and signature of the board chair in the upper right corner. Do not participate in this study if the stamped date is older than one year.

I have read this informed consent document. The risks and benefits have been explained to me. I agree to take part in this study.

____

Please Print Your Name

________________________ ____________________

Participant's signature Date