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# The Development of a Motion Sensing Device for Use in a Home Setting

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# The Development of a Motion Sensing Device for Use in a Home Setting

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# Abstract

Parkinson's disease (PD) is the second most prevalent neurodegenerative disease, with over 10 million individuals diagnosed with PD world-wide. The most common symptom characterized by PD is tremor. Tremor is an involuntary oscillatory motion that most prominently occurs in upper limb, specifically in the hand and wrist that has a measurable frequency and amplitude. This thesis aims to evaluate the usability and functionality of a tremor sensing device designed to collect quantitative data on individuals with PD. The designed device uses 23 commercially-available inertial measuring units (IMUs) located between 21 joints: distal interphalangeal (DIP) joints, proximal interphalangeal (PIP) joints, Interphalangeal (IP) joint, metacarpophalangeal (MCP) joints, carpometacarpal (CMC) joint, trapeziometacarpal (TMC) joint, radiocarpal joint, and the elbow joint. The IMU sensors include a 3 degree of freedom (DOF) accelerometer and a 3 DOF gyroscope activated during data collection. In specific, this thesis evaluates the device with trials on healthy participants by collecting data in the time and frequency domain during activities of daily living (ADL) over 48 hours in a home setting.

A total of 7 healthy participants were recruited to wear the device in a home setting over 2 days. The linear acceleration and angular velocity signals were captured, which were later used to analyze the data in the frequency domain, similar to if it were for tremor signals. If the voluntary motion signals in the time and frequency domain are close to the accepted values for voluntary motion, the battery life is sufficient, and data is collected effectively, the device functionality will be validated and can be used to capture tremor data.

***Index terms***— IMU sensors, Wearable devices, Tremor, Parkinson's Disease, Voluntary motion

# Lay Summary

Tremor is one of the most common symptoms of Parkinson's Disease (PD), often making it hard to perform daily tasks such as typing, writing, eating etc. Individuals with PD generally do not see a neurologist regularly, and the progression and behaviour of tremor is not examined as often as possible. Neurologists can conduct an assessment on individuals with PD to examine their motor skills, but the assessment is based on visual observation instead of quantitative data in a short time frame, and in a clinical setting. Some individuals may be nervous when visiting a neurologist, or their tremor may not behave the same as it does in a home setting. If their tremor during the assessment does not accurately reflect how tremor acts in their daily life, their symptoms may not be given the most effective treatment. A portable device that can collect motion data from individuals could help capture tremor and better understand how tremor impacts daily living, how often they occur, and other features.

A total of 7 healthy participants were recruited to validate a developed wearable device that uses sensors to collect voluntary motion data in a home setting during daily tasks. The participants were asked to wear the device over 2 days to help validate the functionality of the device, so that in the future it can be used to collect data on individuals with PD in a home setting.

The results of this study show that the data collected for voluntary motion fall within the expected range for linear acceleration and the data can be used to find frequency of movements and power. The same procedure can be followed to analyze tremor data in the future. Some of the sensors had similarities between certain joints on different fingers, so it is possible to eventually use this work as a basis to create more compact designs in the future. In addition, the results from the participants' assessments of the device and trial can be taken into consideration when developing improved wearable devices.

*Dedicated to my dearest mother:*

Heidi Kalsi

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# Nomenclature and Acronyms

## Variables

| | |
|---|---|
| $A$ | Raw acceleration value |
| $A_L$ | Linear acceleration |
| $B$ | Bandwidth of the signal |
| $f_s$ | Sampling frequency |
| $m$ | Calibration parameter matrix |

## Units

| | |
|---|---|
| dps | degree per second |
| g | The acceleration of gravity |
| Hz | Hertz |
| $m/s^2$ | meter per second squared |

## Acronyms

| | |
|---|---|
| 2-D | Two-Dimensional |
| 3-D | Three-Dimensional |
| ADL | Activities of Daily Living |
| CMC | Carpometacarpal |

| | |
|---|---|
| CSV | Comma-seperated Values |
| DIP | Distal Interphalangeal |
| DOF | Degrees of Freedom |
| EM | Electromagnetic |
| EMG | Electromyography |
| FFT | Fast Fourier Transform |
| IMU | Inertial Measurement Units |
| IMMS | Inertial and Magnetic Measurement System |
| IP | Interphalangeal |
| MCP | Metacarpal Phalangeal |
| MEMS | Micro-electromechanical Systems |
| MCU | Microcontroller Unit |
| MDS | Movement Disorder Society |
| PC | Personal computer |
| PCB | Printed Circuit Board |
| PD | Parkinson's Disease |
| PIP | Proximal Interphalangeal |
| PSD | Power Spectral Density |
| RTC | Real-time Clock |
| SD | Secure Digital |
| TMC | Trapeziometacarpal |
| UART | Universal Asynchronous Reciever/Transmitter |
| UPDRS | Unified Parkinson's Disease Rating Scale |
| USB | Universal Serial Bus |

# Chapter 1

# Introduction

Parkinson's disease (PD) is the second most common neurodegenerative disease, with over 10 million individuals diagnosed with PD world-wide [1]. Some of the common symptoms of PD are tremor, bradykinesia (slowness of movement) [2], rigid muscles, posture and balance can limit range of motion, and speech changes. Tremor is an involuntary oscillatory motion that most prominently occurs in the upper limb, specifically in the hand and wrist [3]. Studying tremor is important because approximately 80% of PD patients experience tremor. Tremor generally has a drastic impact on PD patient's daily life, often making it hard to perform tasks requiring fine motor skills because it resembles a shaking motion with rapid movements [4]. The most common areas of the body to experience tremor are between the thumb and index finger, and other regions of the upper limb [5]. The prevalence of PD is expected to grow in the following years, so it is crucial to better understand the symptoms, especially tremor, to lead to better treatment and management of PD.

## 1.1 Background

Studying tremor is important because there is a need to better understand how tremor behaves over time and impacts individuals with PD daily lives to help manage symptoms. The current assessment method used to evaluate tremor was developed by the Movement Disorder Society (MDS). The scale is the MDS- Unified Parkinson's Disease Rating Scale (UPDRS). The MDS-

UPDRS Part 3 examines motor skills and tremor. The MDS-UPDRS is the standard assessment method used to examine the progression of PD and can only be conducted by a neurologist [6]. Individuals with PD usually see a neurologist one time per year. In 2002, 138,728 participants with PD took part in a study conducted by the American Academy of Neurology in the United States. The study found that between 2002 and 2005, only 58% of the participants saw a neurologist over the three-year time span [7].

The MDS-UPDRS Part 3 evaluates motor skills of individuals with PD by looking at speech, facial expressions, rigidity, upper and lower limb movements, gait, posture, resting and postural tremor frequency and amplitude, and other motor skills [8]. A primary limitation to the current assessment method is that these motor skills, specifically tremor, are evaluated based on visual observation instead of a quantitative measurable evaluation [8]. In addition, each of the motor skills and tremor are assessed using a numerical scale based on where the individual's symptoms present during the visit fit best. Since tremor is an oscillatory motion, the exact frequency and amplitude can be measured to provide a more personalized approach to understanding PD tremor and how it impacts a specific individual's activites of daily living (ADL). ADL are the tasks and activities of someones daily life. Another limitation to the current assessment method is that all 3 parts of the exam are typically conducted in less than 30 minutes [9], and part 3, the motor examination should not exceed 15 minutes [8], which is not enough time to fully assess tremor and see how it impacts a person's ADL.

## 1.2 Motivation

Given that the MDS-UPDRS Part 3 examination is conducted in a clinical setting over approximately 15 minutes and can only be conducted by neurologists [6], and individuals are unable to have their tremor assessed regularly by a neurologist, an alternative way to examine tremor progression and behaviour is needed. In addition, capturing tremor data in a home setting during an individual's ADL can display the impact PD tremor has on their daily lives, leading to better treatment and management of PD. The time period of observation with the neurologist may not be enough to fully understand their typical tremor characteristics. When individuals with PD visit

a neurologist, they may be nervous and show varied motor skills and tremor patterns compared to how tremor often behaves in their typical daily lives. The MDS-UPDRS Part 3 estimates tremor and amplitude by visual inspection. Since these features can be measured during an individual's ADL, it can give insight on how tremor can impact daily lives.

Before March 2020, most doctors neurologists appointments were held in person, the COVID-19 pandemic has shifted health care services to predominantly virtual doctor visits. In Ontario, over 50% of health care services were conducted virtually in February 2020 and still over 40% were virtual in March 2021. This new trend has shown that there is a need to be able to monitor health better in a home setting, and understand progression of diseases and symptoms [10]. A study conducted by the St. James Hospital Research and Innovation Office tried to gather feedback on how 212 patients felt visiting a neurologist virtually. The majority of individuals that felt the visit was "not as good" as in person visits were more likely to have a neurological disorder such as PD. This recent shift in health care delivery and individuals with a neurological conditions feelings on virtual visits show that there is a clear need for individuals with neurological disorders like PD to better monitor and track symptoms like tremor in a home setting [11].

Wearable devices with sensors that detect motion can be designed to extract quantitative tremor features in a home setting. Wearable devices that collect tremor data can be validated by testing the functionality and performance of the device on healthy participants in a home setting. A device that collects data from most joints in the upper limb over 48 hours can provide insight on which joints have the most motion data, and what an appropriate minimum data collection could be so that future iterations are more comfortable, less inconvenient, more effective, and capture meaningful data. In extension, validating the device on healthy participants can provide future trials using improved devices on individuals with PD to have a better experience with minimal issues.

## 1.3 General Problem Statement

The most common symptom experienced by 80% of individuals with PD is tremor [6], which can have a drastic impact on an individual's ADL, specifically fine motor skills and tasks that require

precise movement of the upper limb [12]. Since it is only recommended that individuals with PD have an appointment with a neurologist 1 to 4 times per year [13], there is a need to understand tremor behaviour over an extended time period in a home setting.

This work validates a newly-developed wearable upper-limb device that can track motion data and eventually tremor data from 21 joints in the upper limb over an extended period in a home setting over 48 hours. The device captures data from 21 joints so that the most important sensor locations related to voluntary motion and eventually tremor in the upper limb can be identified and used to make more compact and lighter devices in the future. The trials took place over 48 hours because later device iterations can use the data to identify the minimum time that a trial can occur for while still capturing meaningful data, especially regarding PD tremor. The device is validated by collecting voluntary motion data from healthy participants with the same experimental procedure that can later be applied to examine tremor behaviour over an extended period during ADL. This device is the first iteration of its type, so evaluating it on healthy participants can give insight on how the device can be made more comfortable, light, and how joint range of motion can be increased.

## 1.4 Research Objectives

The objective of this thesis is to validate a wearable sensing device that collects motion data from the upper limb so that it can eventually be used to collect motion data from individuals with PD to examine the impact of tremor on ADL and tremor behaviour in a home setting.

The research objectives are:

1. To design a portable, comfortable, and relatively light wearable device that has sufficient battery life to collect data over a two-day period.

2. To validate the functionality of the device by running trials on healthy participants.

3. To validate the ability to collect tremor data in the upper limb.

## 1.5 Thesis Outline

The layout of this thesis is as follows:

**Chapter 1** Introduction: The introductory chapter.

**Chapter 2** Literature Review: Presents a review on voluntary motion, types of tremor, tremor treatment and current research in motion sensing devices.

**Chapter 3** Device Design: Explains the methods used, the device design, how the trials occurred, data processing and how the device was calibrated.

**Chapter 4** Experimental Validation and Methods: Explains how the device was validated on healthy participants.

**Chapter 5** Results and Discussion: Presents and discusses the results from the accelerometer data, gyroscope data, frequency domain data, ADL log, and the Participant Feedback Questionnaire.

**Chapter 6** Conclusion and Future Work: Discusses the impact of this study and what can be done following this study to enhance current research in wearable sensing technology.

**Appendix A** Permissions and Approvals: Includes ethics permission and approval, consent form.

**Appendix B** Participant Trial Form: ADL Log: A blank copy of the Participant Feedback Questionnaire that was completed during trials.

**Appendix C** Participant Trial Form: Participant Feedback Questionnaire: A blank copy of the ADL Log that was completed during trials.

**Appendix D** Letter of Information: A blank copy of the first page of the Letter of Information and Consent Form.

**Appendix E** Linear Acceleration and Angular Velocity: The linear acceleration data for each IMU and angular velocity data for each joint.

# Chapter 2

# Literature Review

## 2.1 Introduction

Research studies can be explored to gain insight on motion signals, developed wearable devices with similar technology, PD tremor, and sensors. A thorough literature review was performed from September 2021 to June 2022 with the Google Scholar search engine and the Omni - Academic Search Tool available from Western Univerisity libraries. The following keywords were explored: Parkinson's Disease, tremor, tremor sensing, voluntary motion sensing, wearable devices, wearable mechatronic devices, IMU sensor applications, wearable sensors and IMU data processing. Literature and studies that discussed current wearable devices with IMU sensors were given priority.

This chapter consists of the following: Section 2.1 discusses voluntary motion and tremor, Section 2.2 explores micro-electromechanical systems, Section 2.3 gives background on IMU sensors, benefits and challenges, and Section 2.4 compares current motion sensing devices that have been developed.

## 2.2 Voluntary Motion and Tremor

Voluntary motion occurs when an individual moves with an intention to act a specific way. Voluntary motion is performed during an individual's ADL. Voluntary motion typically has a frequency of around 1 Hz and is generally less than 2 Hz [14]. Voluntary motion can be measured using

accelerometers and gyroscopes to obtain the linear acceleration and angular velocity for each joint.

Tremor is an involuntary oscillatory quivering motion that occurs in approximately 80% of individuals with PD. Tremor most commonly occurs in the hand and fingers. The most prevalent instance of tremor in individuals with PD is the "pill rolling tremor". This tremor occurs between the index finger and thumb. It appears as if the individual is rolling a pill between the affected fingers [3]. Tremor can also occur in other areas of the body such as in the arm, lower lip, jaw and leg.

Resting tremor is an involuntary oscillatory motion that occurs when a body part is at rest against gravity. Resting tremor usually has a frequency between 3 and 7 Hz and is experienced by approximately 75% of individuals with PD [15]. Postural tremor is the involuntary oscillatory motion of tremor that occurs when an individual holds a position against gravity. Postural tremor has a frequency between 5 and 12 Hz and is experienced by around 60% of PD patients [15].

The most prevalent treatment of tremor is for the individual to take medication. The most common medication prescribed to PD patients is Levodopa, with approximately 88% of PD patients using it [16]. More medications that can be used to treat PD tremor include: Dopamine agents such as Ropinirole, Pramipexole, and Apomorphine, MAO-B inhibitors such as selegiline and Rasagiline, COMT- inhibitors such as Entacapone and Tolcapone, and Anticholinergics such as Triexyphenidyl and Benztropine [16]. If medications are not effective for tremor suppression, PD patients may undergo deep brain stimulation or other surgical options [17].

## 2.3 Micro-electromechanical Systems

Micro-electromechanical systems (MEMS) is a process technology that develops small integrated devices with integrated circuit or batch technology ranging from one micro to a few millimetres [18] to combine electrical and mechanical components. One criterion for MEMS is that they have a mechanical functionality, but the elements in it are not required to move. Some types of MEMS include miniaturized structures, sensors, actuators and electronic circuits. The most prevalent MEMS are microsensors and microactuators, which are categorized as transducers. Microsensors generally converts a mechanical signal to an electrical signal [19]. Some common wearable device

applications of MEMS include smart watches and fitness trackers. The global revenue from wearable devices with MEMS has increased from $31 million USD in 2013 to over $60 million USD in 2016 [20] and is estimated to increase to around 18.2 Billion USD in 2030 [21]. A common type of MEMS device is an IMU sensor, which can measure motion data. are often used in wearable devices due to their small size, low cost, ease of implementation with other electrical systems, and commercial availability. In 2019, the global market size for IMU sensors was $17.34 billion, and is expected to reach over $24 billion in 2027 [22]. IMUs are used in commercially-available devices such as Oura Rings, Fitbits, smartwatches, etc, and are used in a variety of developed wearable devices to conduct research for motion, fitness and clinical applications.

## 2.4 IMU Sensors

IMUs are a type of sensor that can collect motion data. Most IMUs are either 6 degrees of freedom (DOF) or 9 DOF. a DOF is how many independent parameters or ways an object can move through space [23]. In specific, 6 DOF IMUs use an accelerometer and gyroscope, where a 9 D0F IMU contains an accelerometer, a gyroscope, and a magnetometer An accelerometer obtains the acceleration or the change in velocity over the $x$, $y$, and $z$ axis. The acceleration data collected by an accelerometer is often in $m/s^2$ or gravity (g). Accelerometers can also measure gravity as a downward force. To obtain velocity from an accelerometer, the acceleration values can be integrated with respect to time. In addition, if you integrate acceleration values twice with respect to time, the position can be found [23]. A gyroscope is used to measure rotational changes and to report the angular velocity about the $x$ (pitch), $y$ (yaw) and $z$ (roll) axis over a specific time period. The angular velocity is typically in degrees per second (dps) [24].

A magnetometer can help find the orientation using the earth's magnetic field. Magnetometers can detect changes in the earth's magnetic field using the air's magnetic flux density at the sensors location in space, then finds the vector towards the earth's magnetic North [25].

### 2.4.1 Benefits

IMUs are made by many manufacturers and commercially available online, often low-cost, small, lightweight. Their small size makes them very useful for wearable device applications. They can obtain useful motion data such as linear acceleration, angular velocity, and magnetic field strength that can be used to study range of motion, voluntary motion and other movement characteristics. Other features such as amplitude, frequency, position, and velocity can be extracted from data processing.

### 2.4.2 Limitations and Challenges

IMU drift is the process of small measurement errors, mostly from the gyroscope, accumulating and causing slow changing variations in angular velocity over time. The gyroscope in IMUs cause drift over time because the initial zero reading causes signal noise and accumulate as rotation or angle drift over time. The IMU orientation is found by taking the integral of the angular velocity, but the initial zero readings lead to a drift when estimating the orientation over time [26].

One way to reduce IMU drift is using a magnetometer to determine the correct heading by measuring the surrounding magnetic field. This method works better outside because the Earth's magnetic field is prominent, but is not as effective in an indoor setting [18].

Another way to reduce the drift caused by gyroscopes is to use a low-pass filter or a Kalman filter during data processing. A low-pass filter removes noise by allowing signals that are less than a specified frequency to pass, and removes signals with frequencies above the cut-off. A Kalman filter is an estimation algorithm that uses an estimate of system state and combines accelerometer, gyroscope and magnetometer data to obtain a more accurate representation of orientation and position [27].

This data can be processed to eventually yield tremor and voluntary motion frequency and amplitude. Since many commercially-available IMUs are small and light weight, they can be used in the design of wearable devices that can be worn to obtain motion data [25].

## 2.5 Motion Sensing Devices

A variety of motion sensing devices have been developed by researchers to better understand voluntary motion and tremor for a variety of reasons such as rehabilitation purposes, studying movement in arthritis patients, classifying specific tasks, etc. Some of the devices that have been developed are summarized in Table 2.1. Based on the literature reviewed, none of the devices that have been developed collect data from every joint in the hand, except the proposed wearable sensing device. In addition, they are not all portable, and most are used for data collection in a laboratory setting.

Lin et. al [28] developed a wearable device that collects movement data to better understand hand kinematics for medical applications like rehabilitation. The proposed device has a modular design with flexible printed circuit boards (PCBs) to make hand movement easier while wearing the device. The IMUs are placed on a single-layer thin glove without a layer covering the hardware. The glove consists of 18 9 DOF IMU sensors that can transmit the raw data using Universal Asynchronous Receiver/Transmitter (UART) or a Bluetooth module when powered by a battery. A major drawback to this design is that the hardware is not covered so it is more likely to be damaged during trials. The proposed design is shown in Figure 2.1.

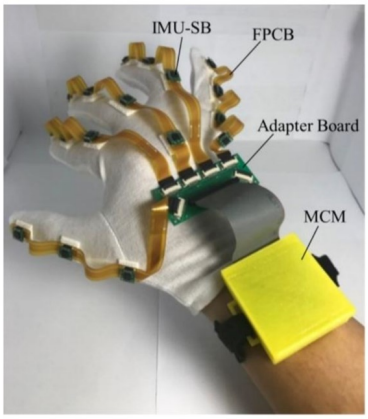


Figure 2.1: The device developed by Lin on a participant [28].

Kortier et. al [29] developed a sensing glove to accurately study three dimensional hand and finger kinematics. The glove uses inertial and magnetic measurement systems (IMMS), a combination of inertial sensors and magnetic sensors, like IMUs. The glove hardware consists of 16 6 DOF IMU sensors and 3 magnetometers. The hardware has flexible PCB's connecting the sensors, and they are taped directly to the skin to hold them in place. The hardware does not have a glove layer under it or covering it. The device can communicate via UART or Bluetooth. One of the limitations to this device is that the wires restrict motion of trial participants [28]. The developed glove is shown in figure 2.2.

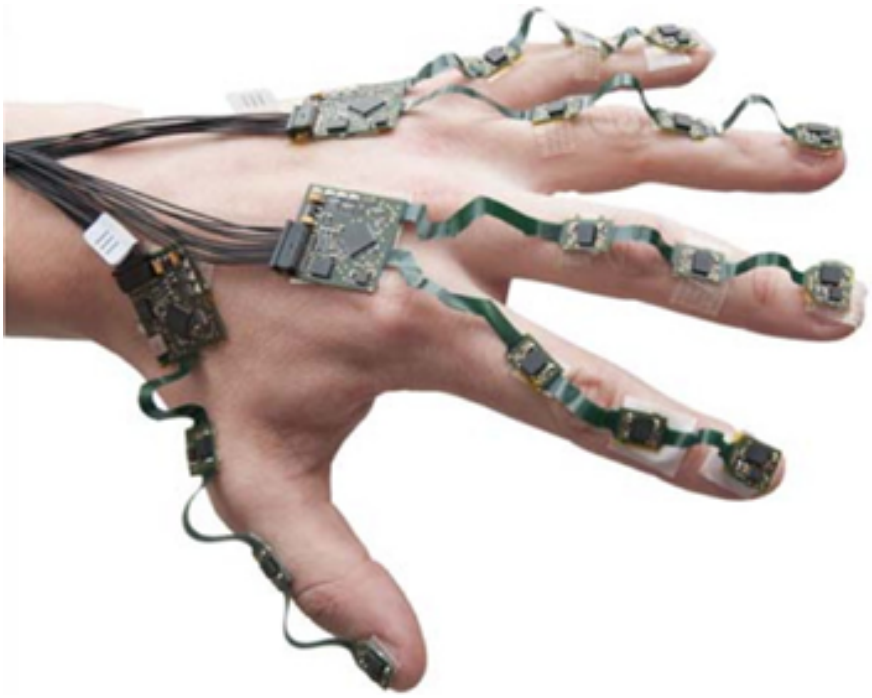

Figure 2.2: The proposed design by Kortier worn by a participant[29].

Connolly et. al [30] developed a glove that senses movement in the hand to quantify joint motion on individuals that have rheumatoid arthritis. The hardware consists of a large PCB that sits on the dorsal side of the hand and covers a large area of the metacarpal joints, 14 PCBs to surround the joints in the fingers, and flexible technology to connect the PCB's. The device consists of 16 9 DOF IMU sensors. The glove can save data to a secure-digital (SD) card or communicate via UART. Some limitations to this design is that there is a relatively large PCB covering most of the dorsal side of metacarpal joints which could be uncomfortable and limit motion, and the

hardware components are not covered so they could be subject to damage during trials. The glove hardware developed by Connolly et. al is shown in Figure 2.3 and the glove design is shown in Figure 2.4.

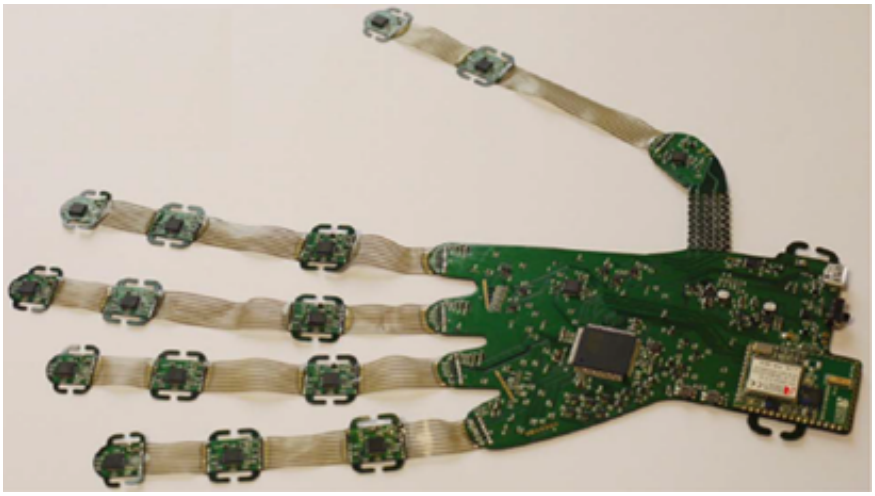

Figure 2.3: The proposed design by Connolly that participants wear during trials to collect data [30].

Figure 2.4: Connolly's proposed design hardware inside the glove that participants wear during trials [30].

Fang et. al [31] proposed two wearable devices, one for each hand, to capture movement data and identify what gestures are being performed during movement. The goal of these gloves are to apply the data obtained to rehabilitation, sports, and the animation industry. The device consists of 18 9 DOF IMU's per hand, on both hands. The hardware is placed on top of a single layer glove, and there is not a layer of material covering the hardware. The gloves use Bluetooth to communicate the data in a clinical setting. A major drawback to this design is that since it is not modular, if one of the IMUs stopped collecting data or got disconnected from the device, all of the IMUs would stop collecting data and would not be able to operate. The devices proposed by Fang et. al is shown in Figure 2.5.

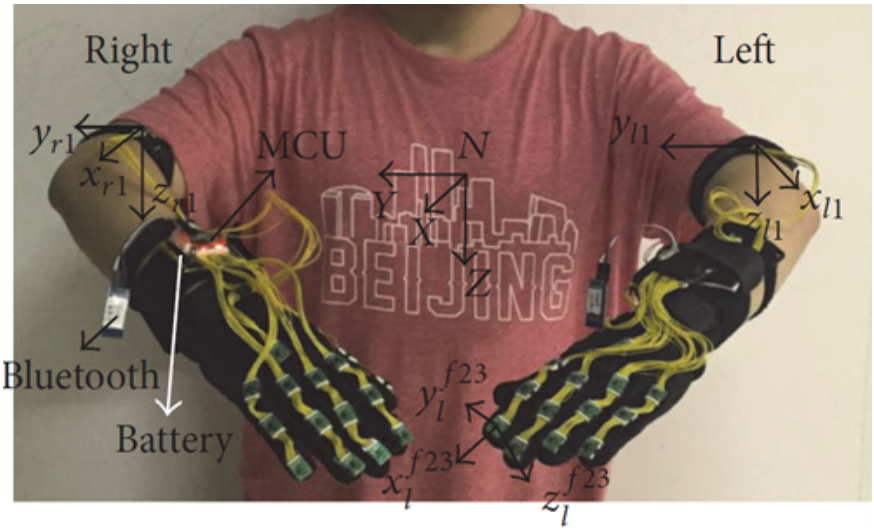


Figure 2.5: The proposed devices by Fang worn on both hands by a participant [31].

Zhou developed a wearable mechatronic device to collect tremor motion data and suppress tremor on individuals with PD. The device was tested on 18 individuals in a laboratory setting. The participants were asked to complete 5 motor tasks, and they were asked non-related questions to distract them from suppressing their tremor. The device consists of 5 9DOF IMUs, 5 electromagnetic (EM) trackers to collect data from the index finger MCP joint, the thumb MCP joint and the wrist joint [32]. The data is sent to a PC through serial to universal serial bus (USB). There is also electromyography (EMG) data that communicates with a personal computer (PC) by Bluetooth. The hardware of this device is places directly onto the skin and strapped in place,

as shown in Figure 2.6.

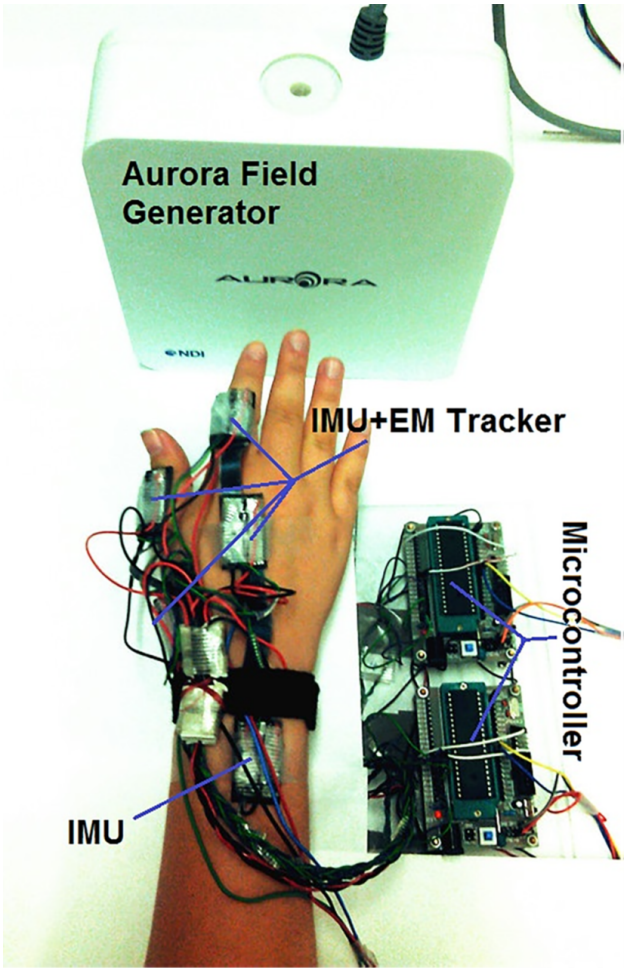


Figure 2.6: The experimental setup and a participant wearing the device proposed by Zhou [32, 33].

Papaopoulos et. al used IMUs embedded in a smartphone to collect accelerometer data on healthy participants and individuals that experience tremor. The recordings occur in the wild, and collect linear acceleration signals in the hand used to answer the phone. A maximum of 75 seconds of data is collected during each phone call made. The data and timestamps were stored locally and transmitted wirelessly on a server when there was WIFI. This data was used to train a deep multiple-instance learning approach model [34].

Das et al. developed a system to track PD motor symptoms such as tremor and bradykinesia in a home setting over 4 days. The system consists of 5 3 DOF accelerometers that were strapped to the wrists, ankles and the waist. Participants wore them during ADL in the day, and the data was saved in real time. The device batteries were charged at night. Participants were also asked to log their symptoms and time of occurrence, and when medication was taken for PD within a 20 minute range. The data collected from this trial was used to propose a multiple-instance learning approach that can detect PD symptoms.

Table 2.1: The average time spent on ADL from greatest to least.

| Paper | Sensor Type | Number of Sensors | Number of Joints to Collect Data From | Data Collection Capability | Device Trial Location | Limitations |
|---|---|---|---|---|---|---|
| **The Development of a Wearable Sensing Device for Use in a Home Setting** | 6 DOF IMU's | 23 | 21 | Data saved to SD card or UART | Home Setting | The device is two pieces (glove and battery pack) and some ADL are difficult to perform during wear. |
| **Design of an Inertial -Sensor-Based Data Glove for Hand Function Evaluation** | 9 DOF IMU's | 18 | 13 | Bluetooth or UART | Laboratory Setting | The hardware is not covered so they could get damaged during trials. |
| **Assessment of hand kinematics using inertial and magnetic sensors** | 6 DOF IMUs and Magnetometer | 16 IMUs and 3 magnetometers | 15 | Bluetooth or UART | Laboratory Setting | Wires restrict participant motion. |
| **IMU Sensor-Based Electronic Goniometric Glove for Clinical Finger Movement Analysis** | 9 DOF IMUs | 16 | 10 | Data saved to SD card or USB connection to PC | Clinical Setting | Movement and comfort are restricted by a large PCB covering most of the dorsal side of metacarpal joints and the hardware is not covered so they could be damaged during trials. |
| **Development of a Wearable Device for Motion Capturing Based on Magnetic and Inertial Measuring Units** | 9 DOF IMUS or MMUs per hand on both hands | 18 per hand and 36 total | 9 per hand | Bluetooth | Clinical Setting | Not modular so if one IMU is broken then the system can't operate. The hardware is not covered so they could be damaged during trials. |
| **A Wearable Mechatronic Device for Hand Tremor Monitoring and Suppression** | 5 9DOF IMUs and 5 EM trackers | 5 | 3 | Connection to PC and Bluetooth | Laboratory Setting | It is not portable, there is not a layer of fabric covering the hardware, and the hardware is not incorporated into a glove. |
| **Detecting Parkinsonian Tremor From IMU Data Collected in-the-Wild Using Deep Multiple-Instance Learning** | 1 3 DOF accelerometer in a mobile phone | 1 | 1 | Data transferred to PC after when in WIFI | Outdoors | The recordings are only 75 seconds each, and the device needs WIFI to transmit the data. |
| **Detecting Parkinsons' symptoms in uncontrolled home environments: A multiple instance learning approach** | 5 3 DOF accelerometers | 5 | 3 | Continuously logged data as it was collected | Anywhere the participant performs ADL | Participants were required to charge the battery at night and there were 3 devices to wear (ankle, wrist, and waist). |

## 2.6 Conclusion

IMU sensors are an effective way to collect movement data such as voluntary motion and tremor. Since tremor is the most common symptom of PD, it is important to develop a device that is capable of collecting data on tremor to analyze tremor behaviour during an individuals ADL. Developing a motion sensing device and validating it on healthy participants is a helpful starting point to eventually better understand tremor. The developed device can later be improved and prototypes that are lighter, more comfortable and that focus on the most common joints impacted by tremor can be created. IMUs that contain an accelerometer and gyroscope are suitable to collect motion data such as voluntary motion and tremor.

Studying motion sensing devices that have been developed can provide insight on what limitations can be expected when developing a novel device, and what strengths should be incorporated. After reviewing the literature, the goal was to create a modular device that can still provide data if one of the IMUs or other components stopped working, with small PCBs and IMUs, that is portable and protects the hardware from being directly exposed during trials.

# Chapter 3

# Device Design

## 3.1 Introduction

Studying the literature on other developed devices and systems that are designed to track motion data provide insight on what could be improved and what could be re-implemented in a new system to effectively collect motion data. Most of the proposed systems in the literature are for use in a laboratory or clinical setting, so data can be transmitted directly to the PC with a wired connection. Since the trials for this project occur in a home setting, the device must be portable, have sufficient battery life, and must easy enough for participants to don and doff. The proposed device consists of custom-designed and commercially-available electrical hardware, the sensors placed in specific locations on the upper limb, developed firmware to interface the different electrical components with each other, a designed glove and sleeve, and a way to hold the battery pack.

## 3.2 Design Requirements

The trials are conducted in a home setting over a two-day time frame. In order to successfully collect data over this time, the device must be portable, easy to don and doff, lightweight, comfortable, and durable. The device needs to be portable because participants will transport it to their home-setting and wear the device where their ADL occurs. Due to the need for portability,

the device must have sufficient battery life to withstand two days of use. The participants should be able to freely perform ADL, so the device cannot be wired to a PC to be powered or to save the data. The device needs to collect data from most of the upper limb, so the device collects data from 21 joints, which will require 23 IMU sensors. If data is collected from most of the upper limb, it will provide complete tremor data from a variety of different joints to analyze in the future. The device should be easy to don and doff because the participants need to put the device on independently and remove the device after their trial without damaging the device. The device should also be light and as comfortable as possible because the participants are required to wear it for most of their day, for two days. If it is too heavy or uncomfortable, it could prevent individuals from performing some ADL or lead to participants wearing the device for shorter periods. The device needs to be relatively durable because it needs to withstand the ADL performed for two days, taking the device on and off, and wear and tear.

## 3.3 Hardware

The developed device consists of a LPC1768 microcontroller unit (MCU) (NXP Semiconductors) that is interfaced with 23 commercially available LSM6DS1 IMU sensors (ST Microelectronics) soldered onto 23 custom-designed printed circuit boards (PCB's), including 6 different PCB variations of boards that were ordered online from JLCPCB.com, a DS1307 real-time clock (RTC) module (Maxim Integrated), a micro-SD card module (Geekstory), powered by a 5V battery pack (EAFU) and connected with 32-gauge wires. The LPC1768 MCU was selected because it had many pins to connect all of the IMUs to their own chip select pin, as required for the SPI protocol. In addition, it was compatible with both SPI and I2C protocol, which were both needed for the system. IMU sensors were selected because they have an accelerometer and gyroscope that can be used to obtain linear acceleration and angular velocity data, which can be processed to extract meaningful tremor characteristics. The LSM6DS1 IMUs were selected because they were commercially-available at a low cost, they are easy to implement into the system, and they are small in size. The PCBs were custom designed so that they could be small enough to fit on the hand in the locations selected, and so that they could be designed in a way that could reduce

the amount of electrical wires used, and some connections such as the SPI bus wires could be shared. The DS1307 RTC was selected because it was low cost and easy to implement with the MCU selected. The battery pack was selected because it is rechargeable with a USB A to USB C cable and can be easily removed from the device by unplugging the USB A side of the cable. The battery pack has a capacity of 10,000 milliampere/hour (mAh) and has a LED display of its present battery level in percent. The Micro-SD card module was selected because it was small in size, light and low cost. The custom-designed PCBs can be seen in figure 3.1. The IMUs, micro-SD card, and RTC are connected to the MCU as shown in Figure 3.2.

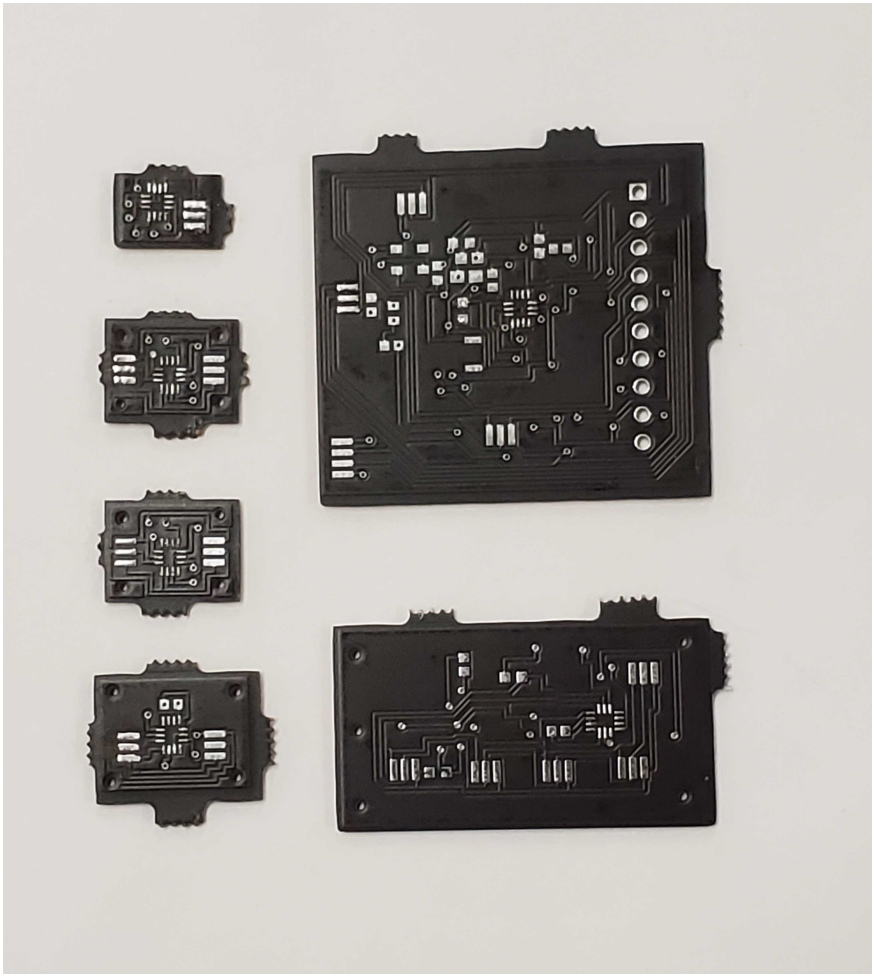

Figure 3.1: The custom-designed PCBs ordered from JLCPCB that IMUs were soldered onto for the device.

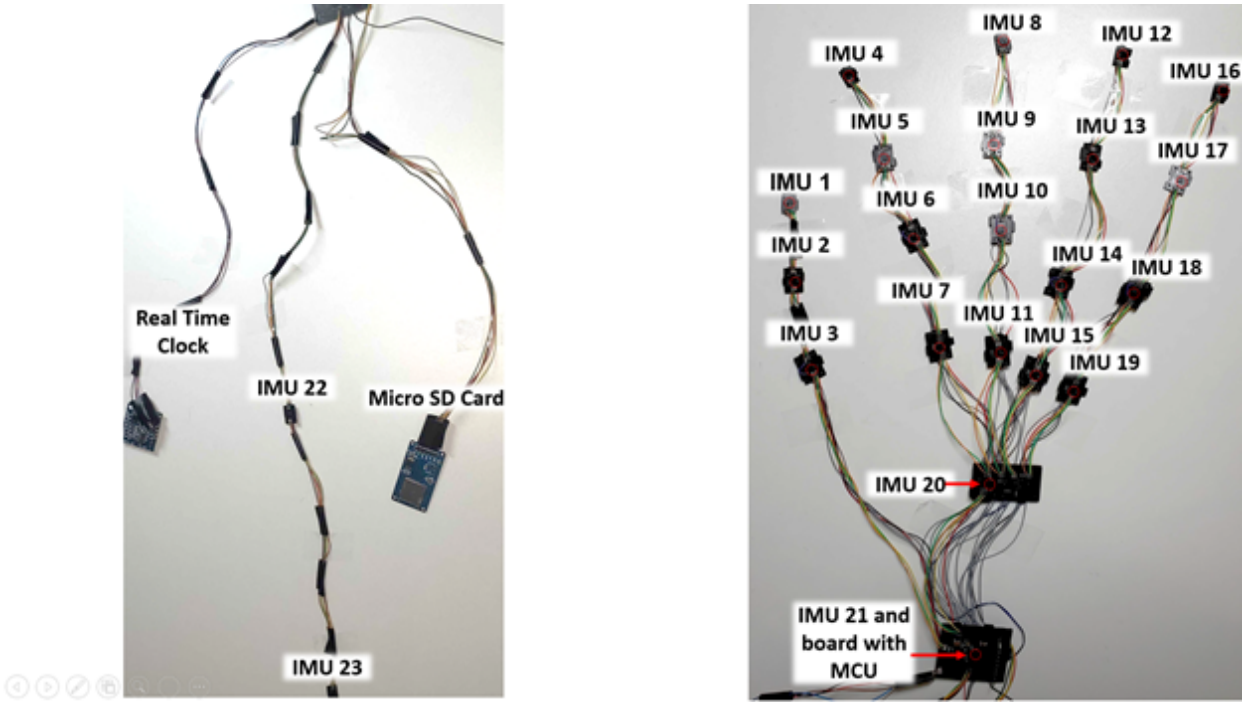


Figure 3.2: The device hardware after the IMUs were soldered on and the components were connected with wires.

## 3.4 Sensor Placement

The IMUs are placed on both sides of the following joints: distal inerphalangeal (DIP) joints of the index finger, middle finger, ring finger and pinky finger, interphalangeal (IP) joint of the thumb, proximal interphalangeal (PIP) joint of the index finger, middle finger, ring finger and pinky finger , metacarpophalangeal (MCP) joint of the thumb, index finger, middle finger, ring finger and pinky finger, carpometacarpal (CMC) joints of the the index finger, middle finger, ring finger and pinky finger, Trapeziometacarpal (TMC) joint of the thumb, radiocarpal joint or wrist, and the elbow joint. The joints of focus excluding the radiocarpal and elbow are shown in Figure 3.3.

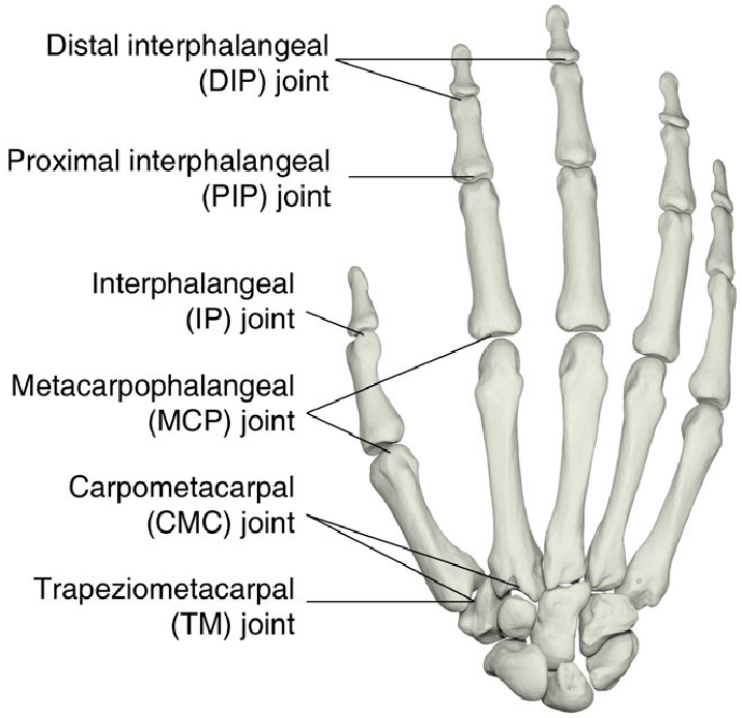


Figure 3.3: The joints of focus in the hand that IMUs surround on the developed device [35].

## 3.5 Firmware Development

The firmware developed allows the IMU sensors, SD card module, and the RTC to communicate with the MCU and it was written in C using Keil MicroVision software. The code first looks to see if the SD card can be detected in the device, to ensure the SD card is inserted into the MicroSD card module. If so, it creates a file on the SD card called "Trial1.CSV" to hold the IMU data. A comma-separated values (CSV) file is created because they are human readable and can be stored efficiently. Once the file is created, it is opened for writing. The timers are then initialized to read and write data to the SD card. The first timer is used to manage reading of IMU data, and the second timer is used to write the IMU data and timer data to the file on the SD card. After timer initialization, there is a check to see if the RTC is detected. IMU data is saved to the file every 35 ms, and the file is closed every 10 s to avoid loss of data in the event of power disruption or if any wires get disconnected. The file is closed every 10 s because the data stored temporarily in a buffer does not get committed to the file until the file is closed. When 15 minutes have elapsed, a new file is created to store new data. The new file follows the same process, the file is closed every 10 s and data being saved every 35 ms. The code is explained in the flowchart in Figure 3.4.

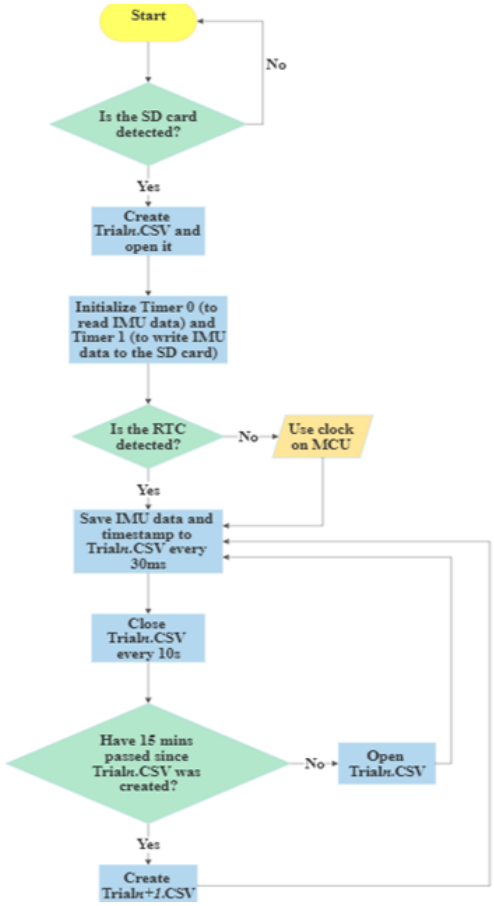


Figure 3.4: A flowchart explaining the code.

Data is saved to the SD card every 35 ms. After trial and error, it was determined that this increment has the least data loss. 10 ms, 15 ms, 20 ms, 25 ms, 30 ms, and 35 ms increments were all explored. Test trials were performed on each increment to collect data for 2 hours, but 35 ms increments were the most reliable and accurate. Since the file needs to be open and closed every 10 seconds, there is a buffer to temporarily hold the data before committing it to the SD card, which can possibly slow down the MCUs ability to keep up with the desired time between data entries. When data was collected every 10 ms, there was approximately 100 ms of data loss when opening and closing the file, meaning that every 10 s, 100 ms of data was lost. The system was able to keep up when less IMUs were considered, but since all 23 IMUs were needed, reducing the number of sensors was not a feasible solution. Voluntary motion can still be detected every 35 ms,

with a sampling frequency of 28.57 Hz. According to the Nyquist-Shannon sampling theorem:

$$f_s > 2 \cdot B \tag{3.1}$$

Where $f_s$ is the sampling frequency, and $B$ is the bandwidth of the signal [36]. Since the maximum frequency of voluntary motion is 4 Hz [14], the sampling frequency should exceed 8 Hz, so 28.57 Hz is a sufficient sampling frequency.

The frequency of tremor is generally less than 12 Hz [15], so a sampling frequency over greater than 24 Hz can capture most tremor. Thus, 28.57 Hz is a sufficient sampling frequency to measure most tremor in future studies.

Tremor has a low frequency band expected to be between 3.5 and 7.5 Hz, and a high band typically between 7.5 and 15 Hz. When tremor is present for individuals with PD, most of the power will be contained in the tremor frequency band, and when it is absent the lower frequencies are expected to be more prominent. Based on previous studies, the tremor typically has the highest PSD between 3.5 and 15 Hz [37]. Accelerometer data in $m/s^2$ and the corresponding power spectral density (PSD) graphs from a research study that compared healthy participants and individuals that experience tremor are shown in Figure 3.5 for resting tremor (RT), postural tremor (PT), and voluntary motion (MT). In this study, individuals with tremor had frequencies predominantly between 3 and 10 Hz. In comparison, most of the frequencies for healthy participants are less than 1 Hz [37]. Using the current sampling frequency of 28.57 Hz, most tremor signals can be captured because signals that are less than 14.29 Hz are detected.

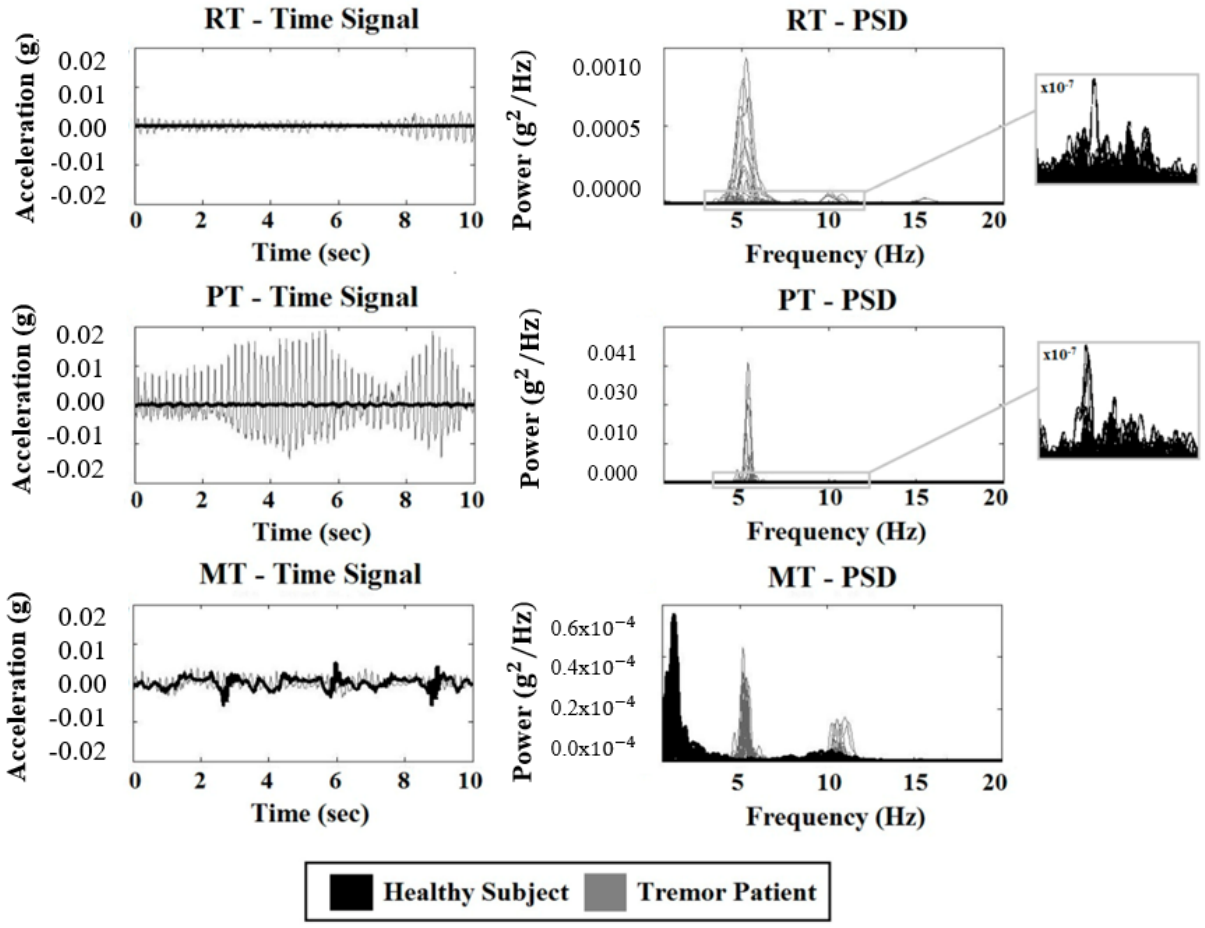


Figure 3.5: Accelerometer data and the corresponding PSD graph for healthy participants and individuals that have tremor for resting tremor (RT), postural tremor (PT), and voluntary motion (MT) [37].

## 3.6 Glove Design

The developed device has a glove component that consists of a finger-less compression glove, industrial strength Velcro, and two-way stretch polyester blend fabric. Compression gloves were selected because they are stretchy, light and breathable to make the base layer of the device as comfortable as possible. The compression glove has Velcro strips attached to it that the PCBs containing the IMUs are attached to. The Velcro strips are used because they allow for the PCBs

to be adjusted based on the distance between the joints of the users hands. There were two gloves developed: one for smaller sized hands and one for larger hands. Individuals participating in trials wore the designed glove on their right hand since all of the study participants had a dominant right hand. The two gloves for different hand sizes can be seen in Figure 3.6. The hardware attached to the Velcro is shown in Figure 3.7. The hardware is covered by the polyester blend fabric with fingertips that attaches to the Velcro strips covering the compression glove. The polyester-blend fabric was selected because one side of it sticks to Velcro, so it covers the hardware, and can be put in place and removed easily. This layer of fabric over the hardware helps keep the sensors in place, adds protection, and prevents the wires on the hand from being exposed. In addition, this layer of fabric provides easy access to the hardware when adjustments are needed between trials. The polyester blend fabric is shown in Figure 3.8. Figures 3.9 and 3.10 show the dorsal and palmar view when the polyester blend fabric is attached to the glove to cover the hardware.

Figure 3.6: The two different glove (base layer) sizes that the hardware attach to with Velcro.

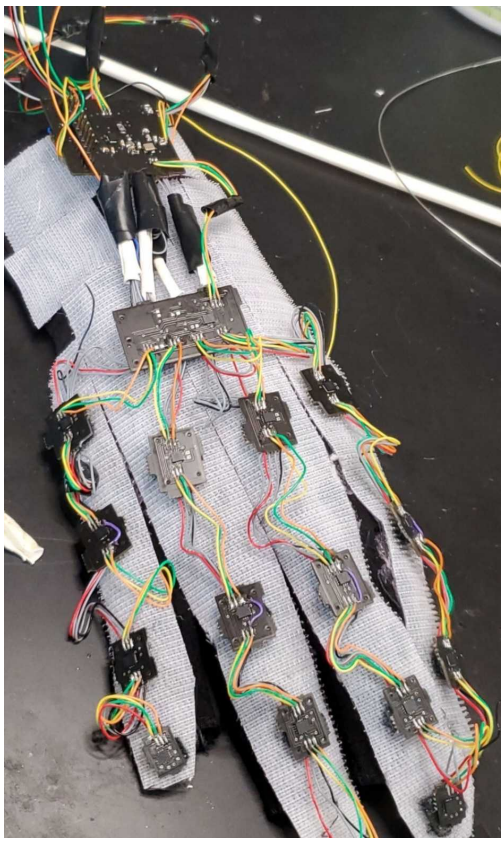

Figure 3.7: The hardware attached to the base layer of the glove with Velcro.

Figure 3.8: The polyester blend fabric that goes over and sticks to the base layer Velcro glove and cover the hardware.

Figure 3.9: Dorsal view of polyester blend fabric on the glove that goes over and sticks to the base layer Velcro glove and cover the hardware.

Figure 3.10: Palmar view of polyester blend fabric on the glove that goes over and sticks to the base layer Velcro glove and cover the hardware.

## 3.7 Sleeve Design

The sleeve component of the device has a compression sleeve that is thin, breathable, and non-slip that sits on the bicep to above the wrist The compression sleeve was chosen because it is light, thin, and has small strips of material on the inside that add friction so the sleeve remains in place. This sleeve has Velcro strips attached to it that 2 IMU sensors, a RTC module, and a micro-SD card module are attached to. Velcro is used because it allows for ease of adjustability to accommodate different arm sizes. The sleeve without the hardware attached is shown in Figure 3.10. Figure 3.11 shows how the hardware attaches to the Velcro on the sleeve. These are covered by a polyester blend fabric to protect the hardware and prevent exposure.

To make the device one piece, the same compression fabric that makes up the sleeve was used to connect the glove and sleeve, and to protect the wires between the main board and elbow by covering them. This fabric contains polyester-blend fabric that sticks to Velcro on the back towards the wrist, and on the back sits on the forearm so that it can attach to the glove and the sleeves Velcro strips to stay in place. This fabric was chosen because it is stretchy, thin, and one of the sides stick to Velcro, keeping the hardware on the Velcro in place and adding a protective layer. This also allows it to be easily removed and used for different sleeve and glove sizes. The fabric connecting the glove and sleeve is shown in Figure 3.12 and 3.13.

Figure 3.11: The designed sleeve without hardware on it.

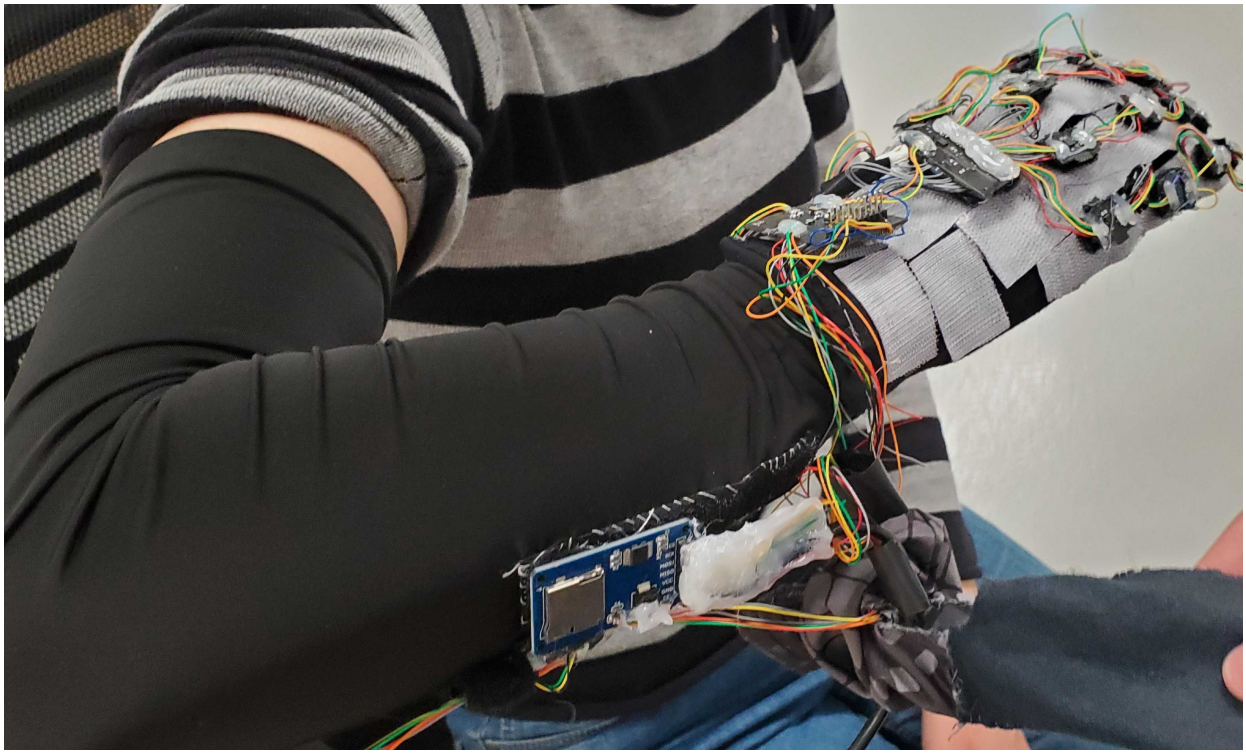

Figure 3.12: The device hardware on the sleeve without the compression fabric over it.

Figure 3.13: The top view of the fabric covering the wires.

Figure 3.14: The bottom view of the fabric covering the wires.

Before the final design was selected, a two-piece design was explored that did not have the compression fabric to connect the glove and sleeve components, and it did not cover the wires that connect the hand and wrist hardware. This design alternative was not pursued because the wires were directly exposed, which could cause the wires to break or get caught on something, and the solder joints would have more pressure on them, leading to the wires getting disconnected. This design also required more effort from the participants because they would need to take the device off very carefully to minimize tension in the wires connecting the wrist and hand or the wires would break.

In addition, an armband (GoZone) is placed over the compression sleeve on the bicep to hold the battery back in place, hold the sleeve in place and prevent possible damage to it. The adjustable armband is shown in Figure 3.14. The armband is fully adjustable in length and stays in place by Velcro on the adjustable fabric strip. The sleeve with the hardware attached and the armband over it is shown in Figure 3.15.


Figure 3.15: The Arm-band to hold the battery pack

Figure 3.16: The designed device on a participant

## 3.8 Advantages and Limitations

The advantages and limitations of the device design are helpful to consider when designing future devices. The advantages of the device are that data can be collected from most of the upper limb joints, the battery pack was sufficient, and the device is easy to don and doff. The device uses 23 IMU sensors and can collect data from 21 joints in the upper limb. This allows for a variety of joint data to be collected for future studies, and can lead to determining what joints are impacted by tremor in individuals with PD. The device battery pack is capable of collecting trial data over 3 days, allowing for the device to be fully portable, require minimal effort on the part of the participant, and it is small enough to sit on the bicep. The device stays powered for the entire trial, even when the participant removes the device overnight. The device is relatively easy to don and doff. After adjustment, the glove and sleeve were attached, and the battery pack was on the bicep in a running armband. After the hardware was fit to the participants upper limb measurements, the participant just needed to take off the armband and take the glove and sleeve component off.

The limitations of the device are that the device was not convenient to wear and the sampling frequency was limited. Some of the participants felt that the device was inconvenient to wear over an extended period of time because the battery pack on the bicep felt bulky. In addition, the device covered the hands and part of the arm, so it could be warm in summer temperatures, especially during ADL that require extensive movement. The device and hardware without the battery pack weighed 260.00 grams, and the battery pack that sat on the bicep weighed 184.27 grams. The device also had covered fingertips, so texting, typing, and other fine motor skills may have felt more difficult. Another limitation to the developed device is that the sampling frequency was limited by saving to the SD card because when saving data at anything less than every 35 ms during testing, data loss occurred. If the device could save data using a higher-bandwidth SD card interface, data could be saved as fast as every 10 ms.

## 3.9 Conclusions

The IMUs are placed on the custom-designed PCBs, and a RTC and micro-SD card module are interfaced with the LPC1768 MCU. The code allows all of the device components to interface with the MCU and for data to be stored directly to the Micro-SD card. The IMUs are placed on each side of the joints of focus. The hardware is placed on a glove and sleeve with Velcro for adjustability, and the wires are covered with fabric to prevent damage. The battery pack sits in an arm band on the bicep that is adjustable allowing for portability. The aim was to make the device as comfortable and lightweight as possible while being able to collect the data effectively.

# Chapter 4

# Experimental Design and Validation Methods

The participants that took part in the trials were recruited by posters at Western University and email advertising. Potential participants were asked to read of the Letter of Information to understand the experimental procedure before participating. If they agreed to participate and met the criteria, an initial visit to the lab to get the device fitted to their hand and arm size was done, and they were sent home with the device for 2 days. There were 2 documents that they were asked to complete and return to later gather qualitative data on their experiences. The quantitative data was recorded and saved to the SD card on the device, then it was later processed and analyzed.

## 4.1 Subjects

A total of 7 healthy subjects participated in this study. The criteria for healthy subjects were to be over 18 years of age, have the cognitive ability to be able to give informed consent, be proficient in English and to not have PD or history of other neurological diseases. The participant ages ranged from 24 to 52, with a mean age of 32. There were 3 male and 4 female participants. The participants wore the device for approximately 10 hours per day for 2 days on the dominant hand during ADL. The experimental procedure was approved by the Health Sciences Research Ethics Board (HSREB), Project 118552. The ethics approval can be seen in Appendix A: Permissions

and Approvals.

## 4.2 Experimental Procedure

Prior to the trial, each participant was given the Letter of Information that contained a consent form, Appendix D. After participants signed the consent form, they attended an initial visit to the Wearable Biomechatronics (WearME) Laboratory, where an overview of study details were explained in person, measurements of the hand and arm were obtained to ensure the device would fit, the dominant hand was noted, the ADL Log and Participant Feedback Questionnaire were provided and explained, and device care instructions were given.

After the initial overview was given, the IMU sensors were custom fit based on the individual's upper limb measurements due to the device's adjustability. The 21 IMU sensors on the glove were positioned around the participant's upper limb joints, then the 2 IMU sensors on the sleeve surrounding the elbow were positioned. The battery pack was placed over the sleeve, and the participant was shown how to put the device on and take if off.

The trial took place within the participant's home setting, where they were asked to wear the device while performing their typical ADL. The participant was asked to either remove the glove or put a rubber/nitrile glove over the device when performing tasks that involve getting their hands wet. The participant was expected to remove the device before showering or submerging the hand, arm, or wrist in water to prevent damage to the electronics. The participant was expected to remove the device during sleep.

The ADL Log was completed by each participant a minimum of once every 2 hours. This log serves to note what activity they were performing, the time of occurrence, and the approximate duration. The Participant Feedback Questionnaire was filled out after the first hour of wearing the device, at the midpoint of the study (24 hours), and after the trial had finished. The Participant Feedback Questionnaire evaluates bidirectionality, wearability comfort, and usability of the glove. It also has a section for the participant to provide any additional feedback.

## 4.3 Data Recording and Processing

The LSM6DS1 IMUs (ST Microelectronics), a DS1307 real-time clock (RTC) module, and a micro-secure digital (Micro SD) card module (Geekstory) were interfaced with the LPC1768 Microcontroller (NXP Semiconductors). The data was saved as a comma-separated values (CSV) file onto a Micro SD card located on the device. A new CSV file was created every 15 minutes to prevent the loss of all of the data from a specific trial if power was lost. The device collects motion data every 35 ms from all 23 IMU sensors. Each data entry consists of the time, IMU number, a 16-bit decimal value for each axis - angular velocity about the $x$, $y$, and $z$ axis, and linear acceleration along the $x$, $y$ and $z$ axis.

## 4.4 Calibration of the Device

Calibration is the process of determining a mapping between the sensor readings and the real-word parameters of interest. The gravitational force is relatively stable and can be used to calibrate the accelerometer portion of the LSM6DS1. In order to use the gravitational force to calibrate the accelerometer, each axis is defined based on its alignment with the axis of gravity.

There are 6 stationary positions that IMU sensors were placed as shown in Figure 4.1, 4.2, and 4.3. The positions for the $x$-axis are $x$-up and $x$-down, the $y$-axis are $y$-up and $y$-down, the $z$-axis $z$-up and $z$-down [38, 39].

$$\begin{bmatrix} A_{cx} \\ A_{cy} \\ A_{cz} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \cdot \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} + \begin{bmatrix} m_{10} \\ m_{20} \\ m_{30} \end{bmatrix}. \tag{4.1}$$

Using the 6 stationary positions, the accelerometer calibration can be written as [38, 39]

$$A_c = A \cdot m \tag{4.2}$$

where $m$ is a matrix with the 12 calibration parameters to be determined, $A$ is a matrix of the raw data collected at the 6 stationary positions, and $A_c$ is the gravitational acceleration [38, 39].

$$\begin{bmatrix} A_{cx} & A_{cy} & A_{cz} \end{bmatrix} = \begin{bmatrix} A_x & A_y & A_z & 1 \end{bmatrix} \cdot \begin{bmatrix} m_{11} & m_{21} & m_{31} \\ m_{12} & m_{22} & m_{32} \\ m_{13} & m_{23} & m_{33} \\ m_{10} & m_{20} & m_{30} \end{bmatrix}. \tag{4.3}$$

Combining equation 4.3 and the 12 calibration parameters yields

$$A_{cnx3} = A_{nx4} \cdot m_{4x3} \tag{4.4}$$

where

$A_c = \begin{bmatrix} A_{c1} \\ A_{c2} \\ A_{c3} \\ A_{c4} \\ A_{c5} \\ A_{c6} \end{bmatrix}_{nx3}$ and $A = \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{bmatrix}_{nx4}$ given that

at the $x$-up position, $A_{c1} = \begin{bmatrix} -9.81 & 0 & 0 \end{bmatrix}_{n1x3}$, $A_1 = \begin{bmatrix} A_{x1} & A_{y1} & A_{z1} \end{bmatrix}_{n1x4}$;

at the $x$-down position, $A_{c2} = \begin{bmatrix} 9.81 & 0 & 0 \end{bmatrix}_{n2x3}$, $A_2 = \begin{bmatrix} A_{x2} & A_{y2} & A_{z2} \end{bmatrix}_{n2x4}$;

at the $y$-up position, $A_{c3} = \begin{bmatrix} 0 & -9.81 & 0 \end{bmatrix}_{n3x3}$, $A_3 = \begin{bmatrix} A_{x3} & A_{y3} & A_{z3} \end{bmatrix}_{n3x4}$;

at the $y$-down position, $A_{c4} = \begin{bmatrix} 0 & 9.81 & 0 \end{bmatrix}_{n4x3}$, $A_4 = \begin{bmatrix} A_{x4} & A_{y4} & A_{z4} \end{bmatrix}_{n4x4}$;

at the $z$-up position, $A_{c5} = \begin{bmatrix} 0 & 0 & -9.81 \end{bmatrix}_{n5x3}$, $A_5 = \begin{bmatrix} A_{x5} & A_{y5} & A_{z5} \end{bmatrix}_{n5x4}$;

and at the $z$-down position, $A_{c6} = \begin{bmatrix} 0 & 0 & 9.81 \end{bmatrix}_{n6x3}$, $A_6 = \begin{bmatrix} A_{x6} & A_{y6} & A_{z6} \end{bmatrix}_{n6x4}$.

The matrix $m$ in Equation 4.2 can be found using

$$m = \begin{bmatrix} A^T \cdot A \end{bmatrix}^{-1} A^T \cdot A_c. \tag{4.5}$$

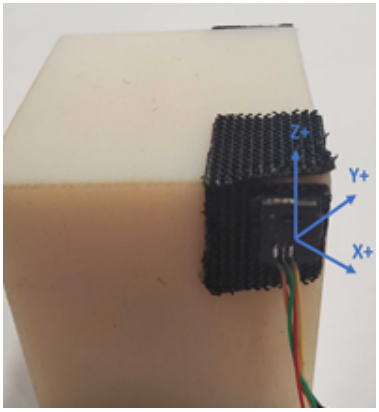


Figure 4.1: The $x$-up stationary position.

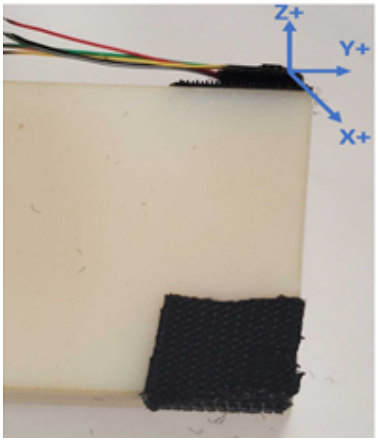


Figure 4.2: The $y$-up stationary position

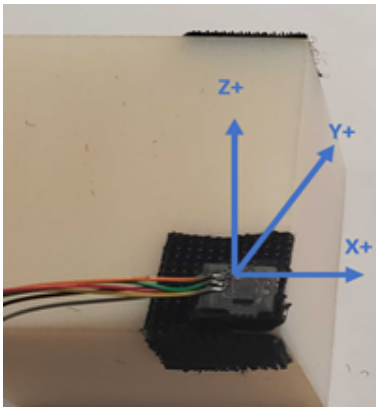


Figure 4.3: The $z$-down stationary position

After the data were collected, the accelerometers were calibrated using the shown methods. They did not need to be calibrated before the trials because the LSM6DS1 IMUs come factory calibrated [40]. After the following calibration procedure was performed, a 2nd order Butterworth low-pass filter was applied to the data to remove noise and extract voluntary motion signals [32]. Signals less than 10 Hz were passed to capture voluntary motion signals. To capture tremor signals in future studies, the data can be calibrated following the same process, and then a 2nd order Butterworth low-pass digital filter can be applied with a cutoff frequency of 14.29 Hz to eliminate noise and pass the meaningful tremor harmonics. In addition the data was analyzed in the time and frequency domain using C++ in Visual Studios.

## 4.5 Conclusions

The 7 subjects in the study followed the specified experimental procedure and data was collected in the setting(s) of their choice. Their activities were logged a minimum of every 2 hours and the time of occurrence and duration. They also provided feedback on the device after 1 hour, 24 and 48 hours. The feedback provided can be used to reflect on limitations and strengths of the device, and can be used in the future to make improvements when making a new device to give participants a better experience. After the data were collected, the accelerometers were calibrated, the data was processed, and preliminary analysis was performed to obtain the results of the study.

# Chapter 5

# Results and Discussion

The quantitative IMU data were recorded continuously throughout the trials and saved to the SD card. When each trial was complete, the battery life remaining was noted, and an SD memory card reader was used to transfer the data to a PC. The data were then calibrated, processed, and a preliminary analysis was performed. The qualitative data were obtained by having participants complete the ADL Log and the Participant Feedback Questionnaire to log their activities and give an evaluation of the device comfort, ability to perform ADL during trials, feelings on the device, ease of donning and doffing, and convenience.

## 5.1 IMU Data and Reliability

The device reliability can be shown by determining whether differences can be detected in resting tasks and movements, time and frequency domain data, the amount of data loss and whether the battery life was sufficient. Based on these factors, the device functionality and usability in a home setting over 2 days can be validated.

### 5.1.1 Individual IMU Validation

Before each trial, all of the IMU sensors were individually validated to ensure they were performing as expected. The IMU sensors are calibrated by the manufacturer, so the following testing validates that the IMUs are working properly. The IMUs were kept in a stationary position on a desk for

30 minutes facing up. The data from the 23 IMUs were captured and displayed in real-time to a PC by serial connection. To validate the gyroscope, the IMUs need to be in a stationary position with minimal movement for a few minutes. When the gyroscope angular velocity values were 0.000 dps in the $x$, $y$, and $z$ position at rest, the accelerometer values were validated. To validate the accelerometer, the IMUs were rotated 45 degrees about each axis so that the IMUs can measure the force of gravity acting on them, until the gravitational vector linear acceleration was 1.000 g in the $z$ direction while facing up resting on the desk.

### 5.1.2 Motion and Rest in the Time Domain

The joints in the upper limb are capable of different types of movements. The thumb CMC, MCP, and IP joints are capable of more motions than the other finger joints. These joints can move by flexion, extension, abduction, adduction, extension and hyper extension. The index, middle, ring, pinky finger finger DIP, PIP, and MCP joint can move by flexion, extension, adduction and abduction. The wrist joint can move by extension, flexion, pronation, supination, radial and ulnar deviation. The elbow is capable of flexion and extension. The DIP joints can move up to 80 degrees, the PIP joints can move up to 100 degrees, the MCP joints can move from -45 to 90 degrees. The wrist joint can move up to 90 degrees in flexion and up to 70 degrees in extension The elbow joint can move up to 150 degrees during flexion, up to 90 degrees during supination, and up to 90 degrees during pronation.

Table 5.1: The motion capabilities of the upper-limb joints.

| Joint | Movement Capabilities | ROM |
|---|---|---|
| **Thumb CMC** | Extension, Flexion, Adduction, Abduction, Extension, and Hyperextension | -10–55 |
| **MCP** | Extension, Flexion, Adduction, Abduction, Extension, and Hyperextension | -10–55 |
| **Thumb IP** | Extension, Flexion, Adduction, Abduction, Extension, and Hyperextension | -15–80 |
| **Index DIP** | Extension, Flexion, Adduction, and Abduction | 0–80 |
| **Index PIP** | Extension, Flexion, Adduction, and Abduction | 0–100 |
| **Index MCP** | Extension, Flexion, Adduction, and Abduction | -45–90 |
| **Middle DIP** | Extension, Flexion, Adduction, and Abduction | 0–80 |
| **Middle PIP** | Extension, Flexion, Adduction, and Abduction | 0–100 |
| **Middle MCP** | Extension, Flexion, Adduction, and Abduction | -45–90 |
| **Ring DIP** | Extension, Flexion, Adduction, and Abduction | 0–80 |
| **Ring PIP** | Extension, Flexion, Adduction, and Abduction | 0–100 |
| **Ring MCP** | Extension, Flexion, Adduction, and Abduction | -45–90 |
| **Pinky DIP** | Extension, Flexion, Adduction, and Abduction | 0–80 |
| **Pinky PIP** | Extension, Flexion, Adduction, and Abduction | 0–100 |
| **Pinky MCP** | Extension, Flexion, Adduction, and Abduction | -45–90 |
| **Wrist** | Extension, Flexion, Pronation, Supination, Radial and Ulnar Deviation | 0–90 (flexion),<br>0–70(extension)<br>0–80 (pronation and supination) |
| **Elbow** | Extension and Flexion | 0 (extension),<br>0–150 (Flexion),<br>0–90 (pronation and supination) |

The difference between when an individual was moving and resting was evident based on the IMU data. Tasks that were likely associated with rest include sitting, phone calls, laying down, and watching television. In comparison, tasks that were associated with movement include typing on a computer, walking, eating, writing, cooking, and driving. Looking at the linear acceleration and angular velocity for the joints can be used to validate the functionality of the device on healthy participants. In the future, data looking at PD tremor can be collected and analyzed to find frequency and power.

The linear acceleration resultant or magnitude for the $x$, $y$, and $z$ direction for sitting, walking, and cell phone use of the middle phalange on the right index finger was compared and example of one randomly-selected participant is shown in Figures 5.1, 5.2 and 5.3. The magnitude of the linear acceleration of the middle phalange on the right index finger during sitting was typically around 0.000 g. The linear acceleration during walking was usually between 0.800 g and 1.310 g. This can be confirmed by comparing the linear acceleration values reported in other studies during tasks involving motion such as finger tapping, similar to texting. In other studies, the linear acceleration during finger tapping was around 10.000 m/s$^2$, which is 1.020 g [41], close to the measured values.

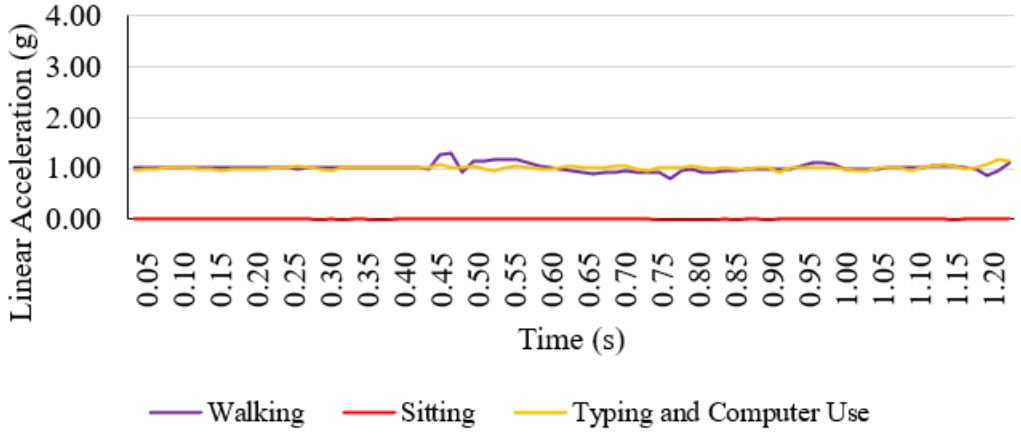


Figure 5.1: Example linear acceleration for the middle phalange bone of the index finger during sitting (resting), typing or computer use, and walking from one participant. Note that, the $x$ axis increases by 0.035 s because that is how often the device saved data to the SD card.

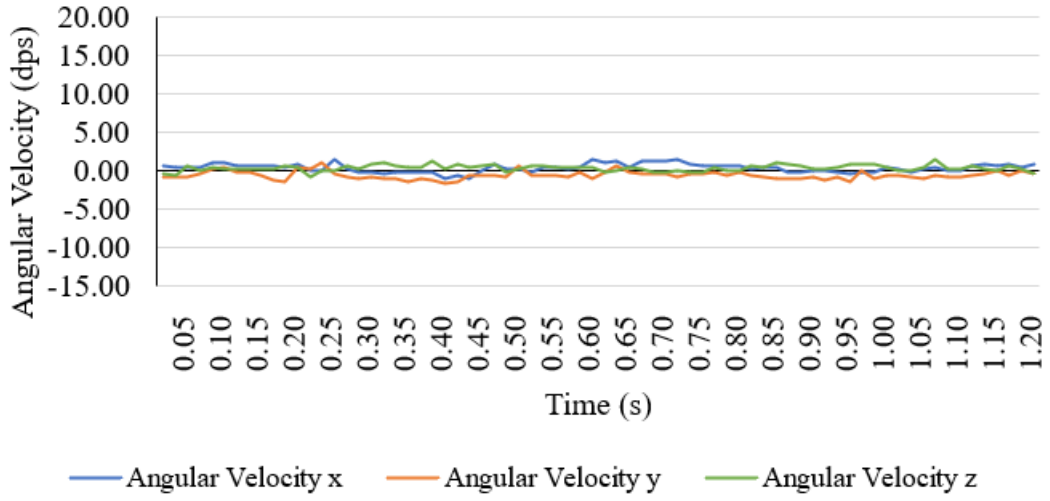


Figure 5.2: Example angular velocity during rest for the index finger DIP joint about the $x$, $y$, and $z$ axis from one participant. Note that, the $x$ axis increases by 0.035 s because that is how often the device saved data to the SD card.

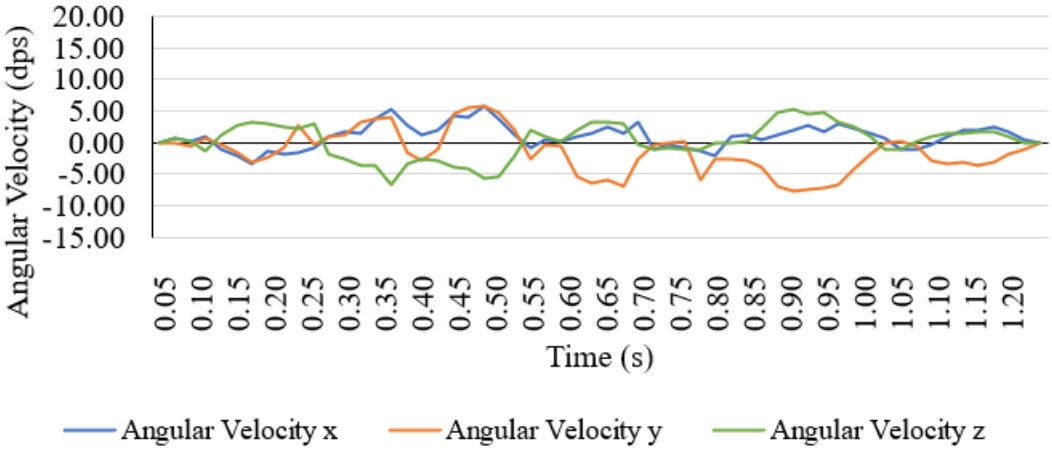


Figure 5.3: Example angular velocity when typing and using a computer for the index finger DIP joint about the $x$, $y$, and $z$ axis from one participant. Note that, the $x$ axis increases by 0.035 s because that is how often the device saved data to the SD card.

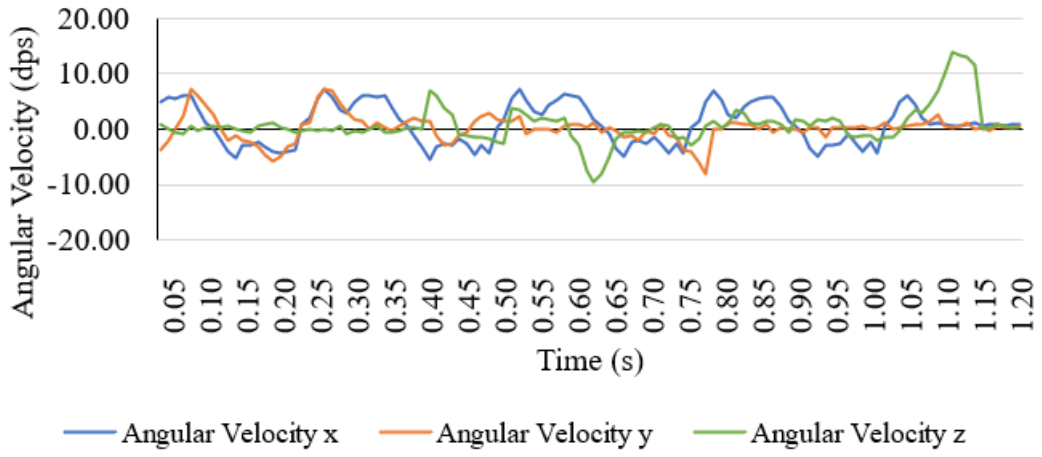


Figure 5.4: Example angular velocity during walking for the index finger DIP joint about the $x$, $y$, and $z$ axis from one participant. Note that, the $x$ axis increases by 0.035 s because that is how often the device saved data to the SD card.

The wrist linear acceleration resultant for the $x$, $y$, and $z$ direction for sitting and walking is shown in Figure 5.4 and 5.5. The average linear acceleration during typing and computer use was 0.129 g. The average linear acceleration during rest for the wrist was 0.014 g. The values obtained in other research studies predict that voluntary motion should have a linear acceleration between 0.000 g and 0.200 g for typing and rest [42]. The average linear acceleration magnitude of the wrist during walking was 1.720 g. Based on the literature, the expected value is around 1.800 g [42] for the wrist during walking; therefore the measured values are relatively similar.

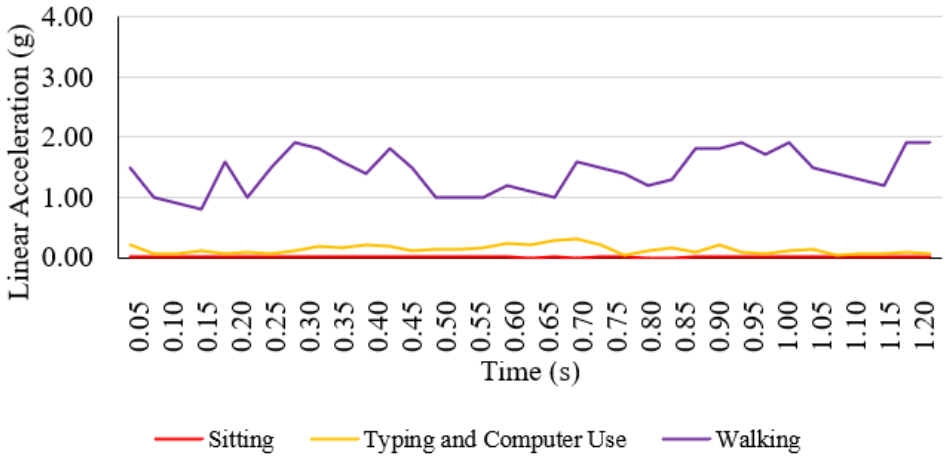


Figure 5.5: Example linear acceleration for the wrist during sitting (resting), typing and computer use, and walking from one participant. Note that, the $x$ axis increases by 0.035 s because that is how often the device saved data to the SD card.

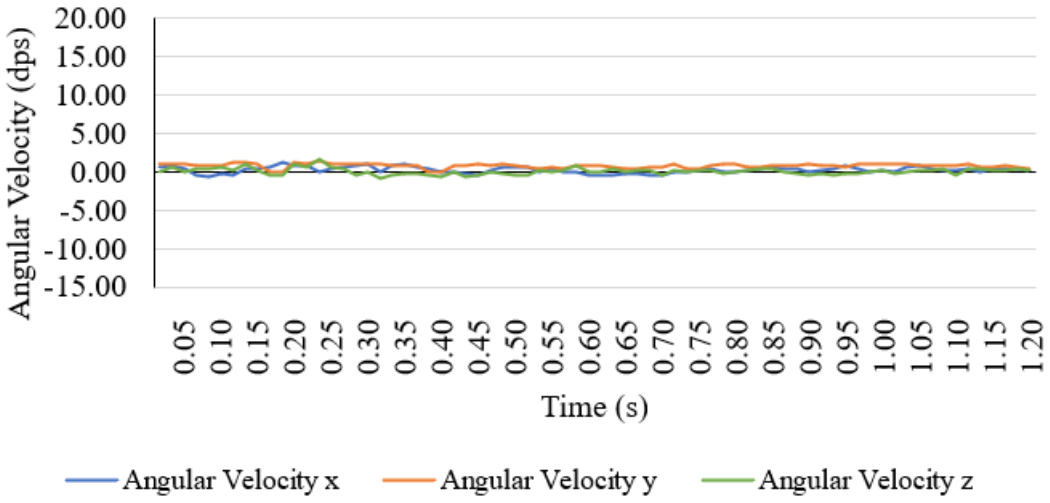


Figure 5.6: Example angular velocity the of the wrist during rest for the $x$, $y$, and $z$ axis from one participant. Note that, the $x$ axis increases by 0.035 s because that is how often the device saved data to the SD card.

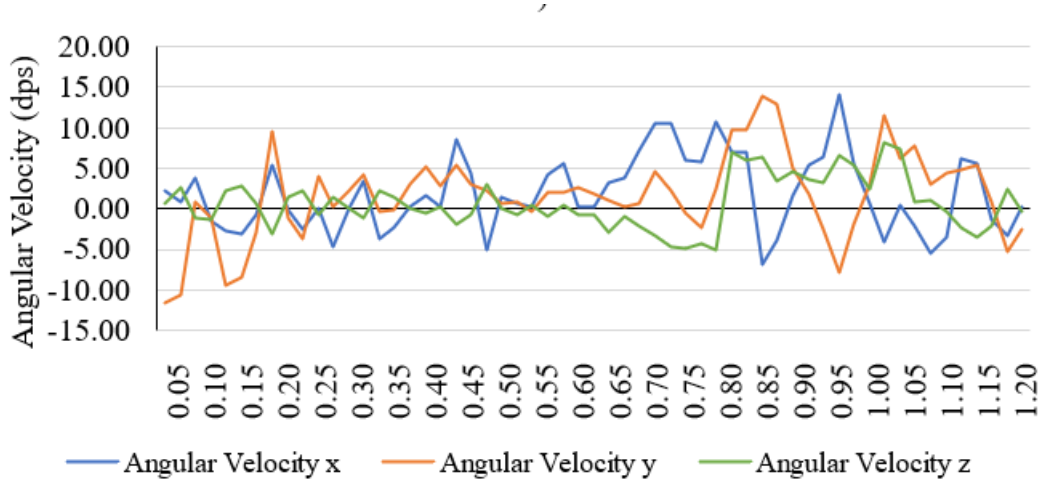


Figure 5.7: Example angular velocity of the wrist during typing and computer use for the $x$, $y$, and $z$ axis from one participant. Note that, the $x$ axis increases by 0.035 s because that is how often the device saved data to the SD card.

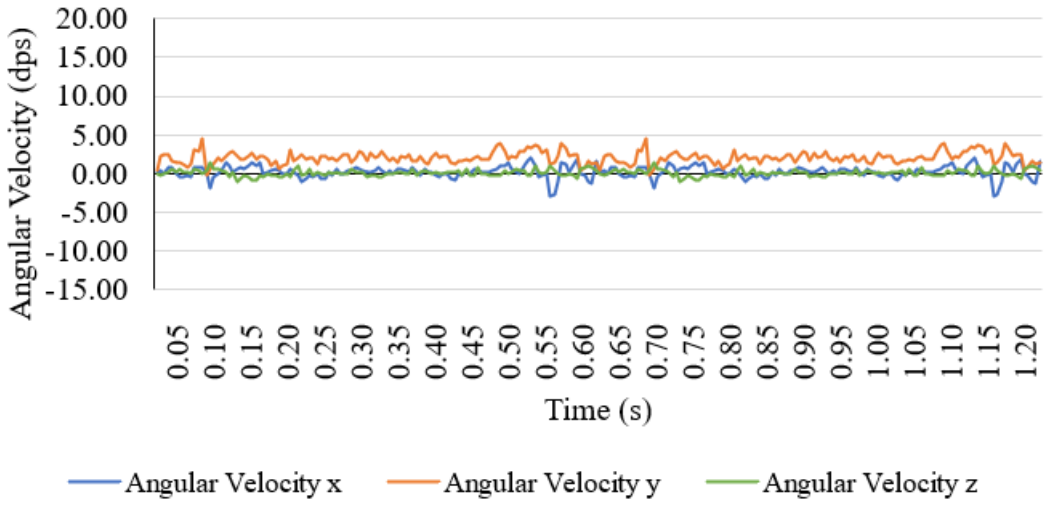


Figure 5.8: Example angular velocity of the wrist during walking for the $x$, $y$, and $z$ axis from one participant. Note that, the $x$ axis increases by 0.035 s because that is how often the device saved data to the SD card.

The minimum, maximum and average magnitude linear acceleration for all of the IMUs during the 7 trials ware detailed in Appendix E. The minimum, maximum and average linear acceleration for the IMU above the elbow was 0.000 g, 3.2 g, and 0.026 g. In comparison, the minimum, maximum, and average linear acceleration for the IMU below the elbow was 0.000 g, 3.019 g, and 0.038 g. The minimum, maximum, and average linear acceleration for the IMU below the wrist is 0.000 g, 4.120 g, and 0.047 g. The minimum, maximum, and average linear acceleration for the IMU above the wrist is 0.000 g, 3.103 g, and 0.146 g. The minimum, maximum, and average linear acceleration for the index to pinky finger were similar for IMUs 4, 8, 12, and 16; IMUs 5, 9, 13, and 17; IMUs 6, 10, 14, and 18; and IMUs 7, 11, 17, and 19. These groups of sensors sit above and below the same joints as the others for each finger. The minimum, maximum, and average linear acceleration for the IMU above the index finger DIP joint is is 0.000 g, 4.100 g, and 0.055 g. The minimum, maximum, and average linear acceleration for the IMU below the DIP joint and above the PIP joint on the index finger is 0.000 g, 3.210 g, and 0.474 g. The minimum, maximum, and average linear acceleration for the IMU below the PIP joint and above the MCP joint is 0.000 g, 2.890 g, and 0.053 g. The minimum, maximum, and average linear acceleration for the IMU below the MCP joint is 0.000 g, 2.870 g, and 0.049 g.

### 5.1.3 Frequency Domain Analysis

IMU data can be analyzed in the frequency domain to extract helpful features of the signal such as frequency and power. The Fast Fourier Transform (FFT) can be used to convert the signals in the time domain to the frequency domain. The FFT analysis splits signals into sinusoids of different frequencies. The FFT should be used with a number of samples equal to an integer to the power of two to obtain the most efficient FFT algorithm [43]. The Cooley-Turkey FFT algorithm is a very common FFT algorithm that was used to convert the IMU data to the frequency domain using developed code in C++. Tremor features such as power and frequency can be extracted from the frequency domain and compared to the values estimated by a neurologist in the MDS-UPDRS Part 3. Voluntary motion typically has a frequency that is less than 2 Hz [14]. The frequency of tremor is expected to be less than 12 Hz. Specifically, the frequency of resting tremor is expected to be between 3 and 7 Hz, and postural tremor is generally between 5 and 12 Hz [15].

PSD is the power in a signal as a frequency function in $g^2$/Hz. It is a helpful comparison in signal processing because the FFT value for acceleration is normalized to frequency so that signals of different lengths can be compared. The PSD was obtained by multiplying the amplitude by the complex conjugate and normalizing it to the sample rate divided by FFT length. Previous research studies have shown that the PSD can be used to understand tremor because as higher tremor signal PSD have higher MDS-UPDRS Part 3 scores, they are logarithmically related ($p < 0.05$) [44]. The low frequency band of voluntary motion is usually less than 3.5 Hz [37]. The PSD compared to frequency is obtained for selected IMUs to confirm that their largest PSD is in the expected frequency range for voluntary motion (less than 2 Hz). The PSD for the index finger middle phalange for one randomly-selected trial are shown in Figure 5.9, 5.10, and 5.11. The index finger middle phalange has peaks between 0 and 1.9 Hz during typing and computer use.The index finger middle phalange is at its max PSD between 0 and 0.5 Hz during rest. The index finger middle phalange is at its maximum PSD between 0 and 1.4 Hz during walking. This is within the normal range, as voluntary motion typically has a frequency that is less than 3.5 Hz during voluntary motion.

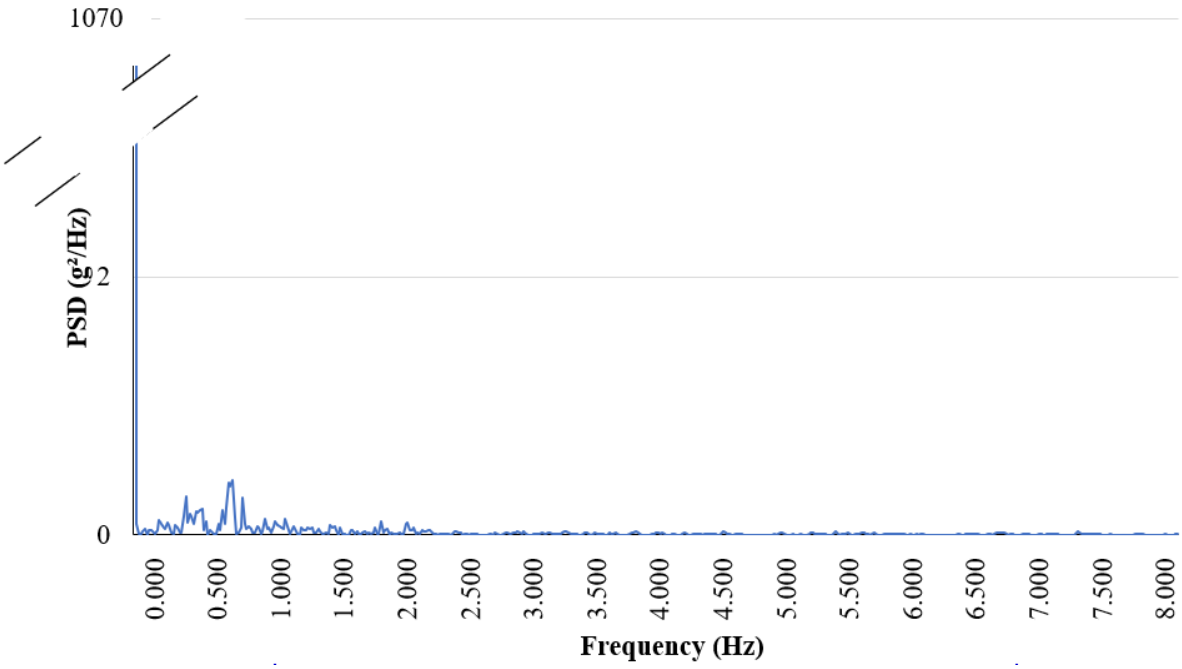


Figure 5.9: PSD graph during walking.

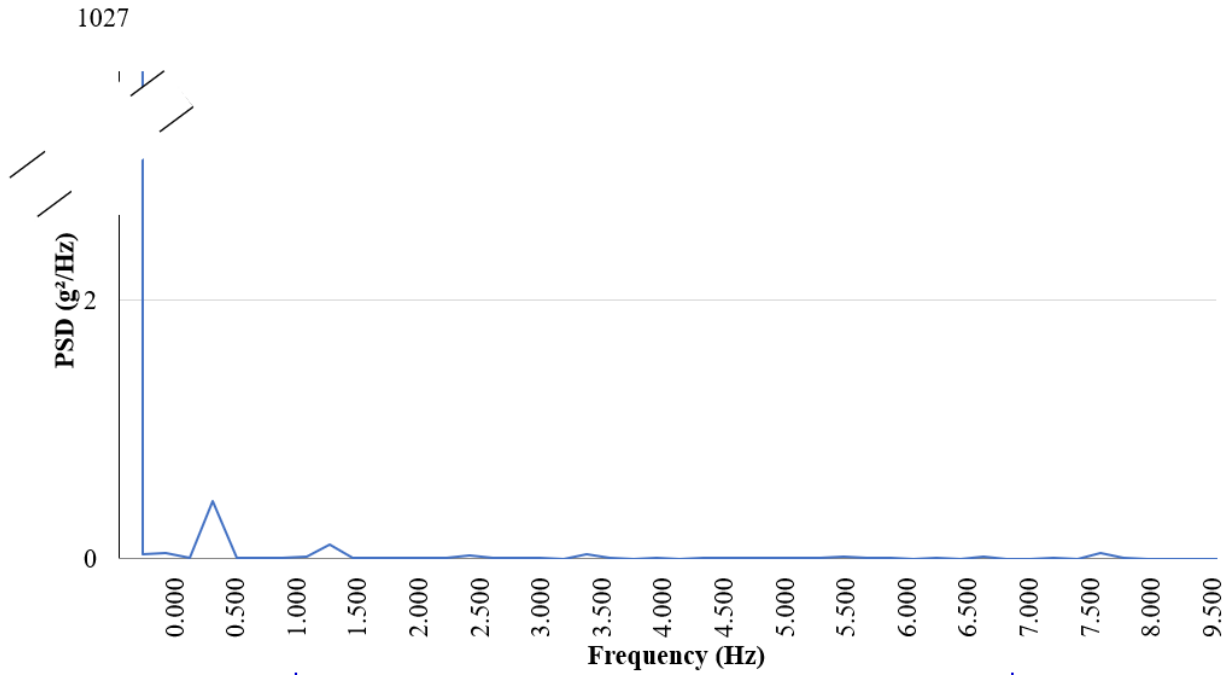


Figure 5.10: PSD graph during sitting or rest.

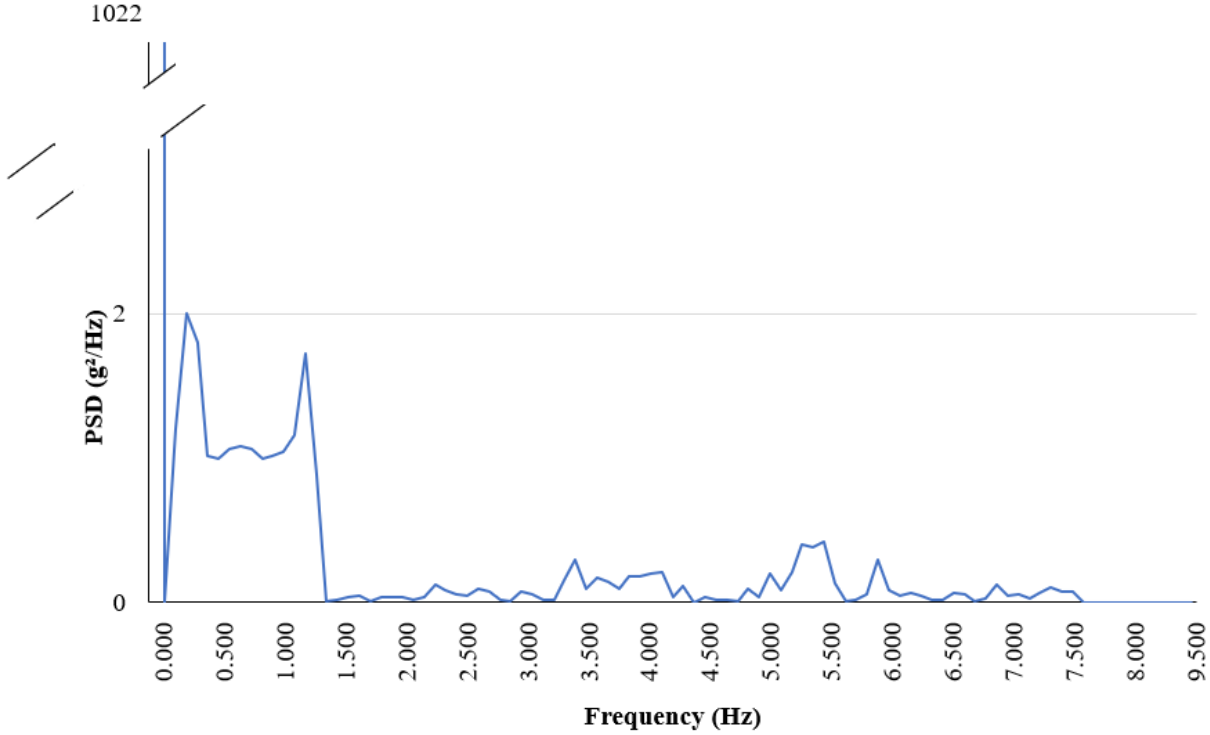


Figure 5.11: PSD graph during typing or using the computer.

### 5.1.4 Data Loss

In some trials, small portions of the data did not save to the SD card as planned. There were some instances where the device stopped creating new CSV files, file corruption occurred, or the SD card was corrupted.

If the device did not create a new CSV file at the appropriate time, the data lost could not be recovered because the file was never created. This likely occurred if there was a power disruption, or wires that connect the microcontroller to the SD card became unsoldered. This happened one time during the first trial. To fix this issue, the wires were resoldered and hot glue was used to cover the solder joints and part of the wires to prevent it from happening again. They remained soldered for the remaining trials.

If the files saved to the SD card were corrupted, the file could be recovered using Recuva software (Piriform) to complete a quick scan and then save the corrupted file. This was able to

recover all of the corrupted files when needed.

If the entire SD card was corrupted, the SD card was scanned and repaired using a command level utility to partially recover files that were on the SD card before it corrupted.

### 5.1.5 Battery Life

It is important that the selected battery pack has sufficient battery life to ensure that the trial can be conducted over 2 days without power disruption. Because the device is worn in a home setting, and the battery is not charged or swapped out over the 2 days, the device must be able to deliver power for the entire 2 days, even when the participant is not wearing the device. The capacity of the selected battery pack was sufficient for every trial. The battery life was noted after each trial was completed. The average battery life remaining after 7 trials was 59%, which indicates the device used less battery capacity than estimated. The device uses an estimated 5707.2 mAh over a 48 hour period. The capacity of the selected battery pack is 10,000 mAh. In the future, a battery pack with lower capacity could be used to supply power to the device. A battery pack with a lower capacity would allow the device to be smaller, lighter, and should be more comfortable to wear.

The calculation for the estimated battery consumption over 48 hours is shown below:

Battery Capacity = (4.3 mA per IMU $\times$ 23 IMUs) + (20 mA per MCU $\times$ 1 MCU)

Battery Capacity = 118.9 mA $\times$ 24 hours per day $\times$ 2 days

Battery Capacity = 5707.2 mAH

## 5.2 ADL Log

The ADL Log documents the tasks that the participants performed during their trials. The participants were asked to log their ADL a minimum of once every 2 hours, but ideally as often as possible. The tasks in the ADL Log can be used to correlate the data to specific tasks being performed at a specific time. It can lead to better understanding an individual's voluntary motion during certain tasks, by providing context to the data. Some participants did not fill out the ADL Log for every activity performed, or they estimated the times at which activities took place. It is most helpful when the participants logged as many activities as they could and recorded the time

of activities. The ADL Log collects entries to help understand expected motion signals and linear acceleration values during certain ADL.

The most common ADL performed during the 7 individuals trials are using a computer or typing, resting or sitting, walking, talking on the phone, and eating or drinking. The task breakdown during the trials can be seen in Table 5.2.

Table 5.2: The average time spent on ADL from greatest to least.

| **ADL** | **Average Time Spent on ADL (%)** |
|---|---|
| Using a computer or typing | 46.99 |
| Time where ADL not logged | 13.93 |
| Resting or sitting | 12.42 |
| Walking | 7.38 |
| Talking on the phone | 4.46 |
| Eating and drinking | 4.24 |
| Other | 2.55 |
| Driving | 1.73 |
| Cooking or food preparation | 1.59 |
| Doing laundry | 1.41 |
| Texing or scrolling on a mobile phone | 1.09 |
| Using the washroom | 0.96 |
| Cleaning | 0.66 |
| Laying down | 0.48 |
| Standing up | 0.06 |
| Outdoor work | 0.04 |

## 5.3 Participant Feedback Questionnaire

During the trials, the participants were asked to complete a Participant Feedback Questionnaire. The questionnaire collected subjective feedback that can be used to understand their experience during the trial, and to gain insight into how future devices could be improved. In addition, the participant's feelings about wearing the device, the ease of donning and doffing, and convenience of wearing the device were assessed after the trial was completed.

### 5.3.1 Comfort

The comfort of the device is subjective and it depends on a variety of factors such as the participant's lifestyle, what their typical ADL consists of, their ability to adjust to wearing the battery pack on the upper arm, and whether they are comfortable with having hardware around their upper limb joints. Since there is not a specific quantitative way to obtain a measure of comfort, the device comfort was assessed by participants after 1 hour, 24 hours, and 48 hours after the trial began using the Participant Feedback Questionnaire. The assessment scale for comfort was a line scale where a rating of 0.00 indicated that the device was very uncomfortable, 5.00 indicated that it was not comfortable or uncomfortable, and 10.00 was most comfortable. The average rating of the 7 participants after 1 hour was 6.00 with a standard deviation of 1.63, after 24 hours was 6.14 with a standard deviation of 1.57, and after 48 hours was 7.43 with a standard deviation of 1.27, as shown in Figure 5.12. The minimum comfort rating after 1 hour is 3.00, 24 hours is 4.00, and 48 hours is 5.00. The maximum comfort rating after 1 hour is 8.00, after 24 hours is 8.00, and after 48 hours is 9.00. Each participant's feedback is shown in Figure 5.13. Based on the feedback provided, it is clear that the participants found the device more comfortable the longer it was worn throughout the trial. The device may take longer than 1 hour to get used to, and performing ADL can be difficult for some at first. After the participants adjusted to wearing the device and knew what to expect, it may have felt easier to perform ADL normally and been more comfortable. Some of the participants feedback that directly relates to how comfort could improve included having a smaller and lighter battery pack on the bicep, relocating the battery pack to a location on the body that can bear more weight such as the hips or in a back pack, having the

fingertips open on the device so that fine motor skills are easier and the fingers feel more "free", and reducing the amount of hardware so that the device is easier to move in.

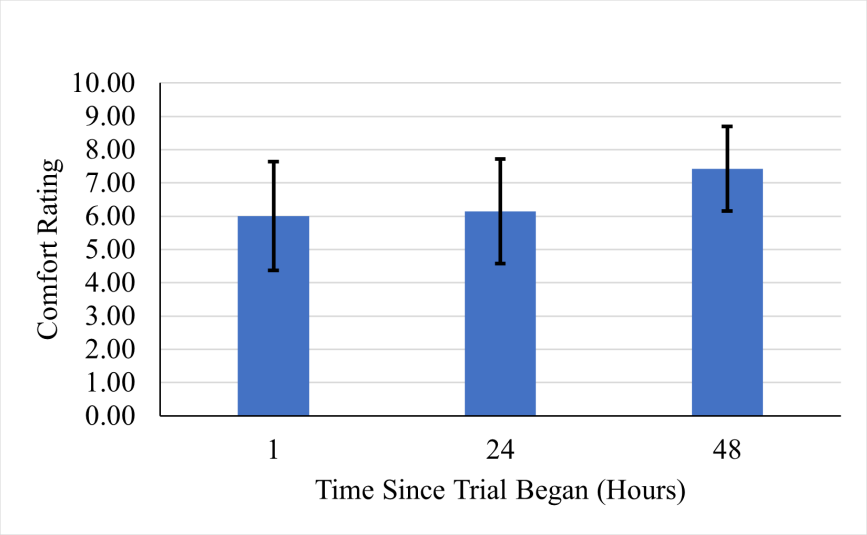


Figure 5.12: The average participant comfort rating after 1, 24, and 48 hours after the beginning of the trial with standard deviation error bars in black.

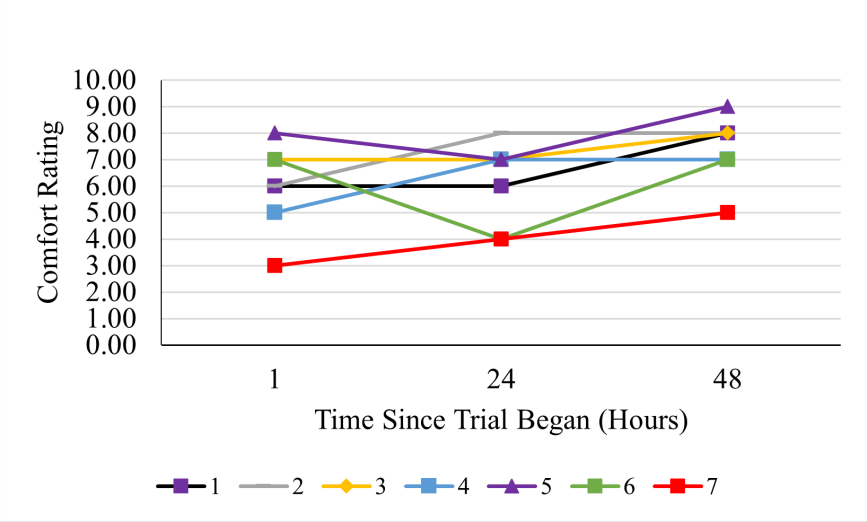


Figure 5.13: A line graph of each participant's comfort ratings after 1, 24, and 48 hours after the beginning of the trial.

### 5.3.2 Ability to Perform ADL

The participants rated their ability to perform ADL during the trial while wearing the device using a scale from 0.00 to 10.00 on the Participant Feedback Questionnaire. Rating the ability to perform ADL as 0.00 implies that the device interferes with every ADL, 5.00 means that the participant can perform around half of ADL, and a 10.00 implies that the participant can perform all of ADL. The average rating for ability to perform based of all 7 participants after one hour was 6.14, after 24 hours was 6.86 and after 48 hours was 7.00, as seen in Figure 5.14. After 1 hour, the minimum rating for ability to perform ADL was 5.00, and the maximum was 7.00, and the standard deviation was 0.69. After 24 hours, the minimum rating was 5.00 and the maximum value was 8.00, with a standard deviation of 0.90. After 48 hours, the minimum ability to perform ADL rating was 7.00, the maximum was 8.00, and the standard deviation was 0.58. Each individual's feedback ratings are shown in Figure 5.15. The average ability to perform ADL increased in time, likely because participants became more familiar with the device and in time it felt easier to perform typical ADL after knowing what to expect. Some of the specific ADL that participants found more difficult to perform included typing, writing, and cooking. The fingertips of the device were able to be lifted to expose the participant's fingertips for typing and using a phone, but an improved device could have the fingertips exposed at all times to make fine motor skills easier.

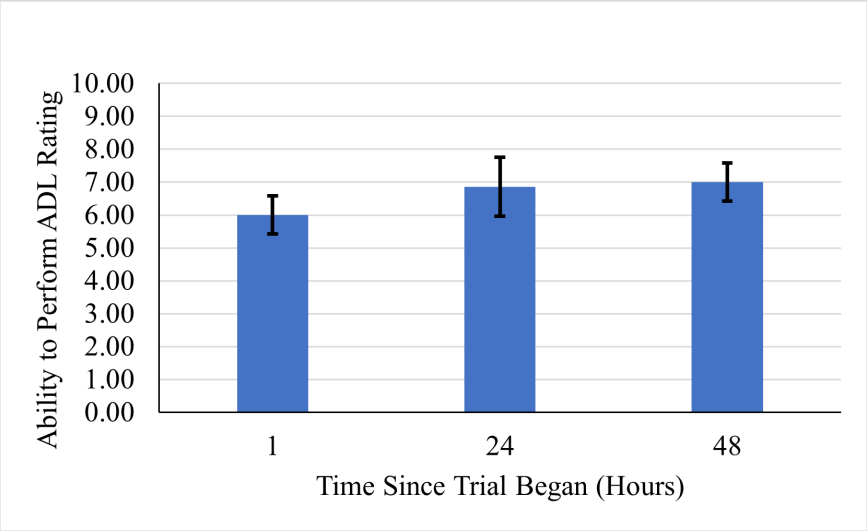


Figure 5.14: The average participant feedback questionnaire ability to perform ADL ratings after 1, 24, and 48 hours with standard deviation bars shown in black.

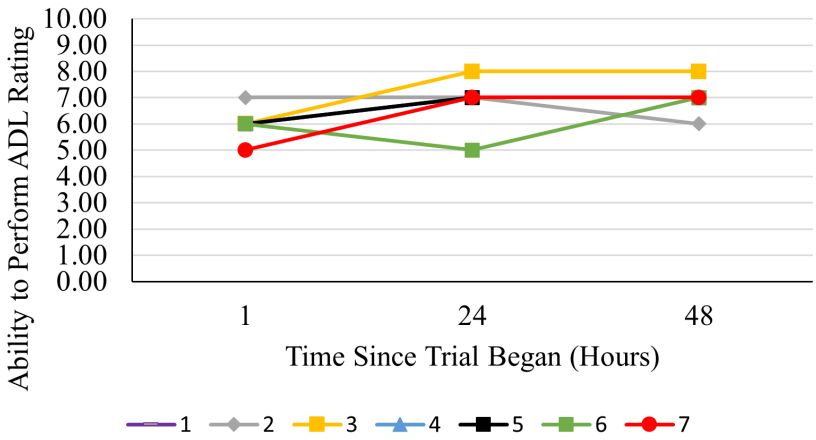


Figure 5.15: A line graph of each participant's ability to perform ADL ratings after 1, 24, and 48 hours after the beginning of the trial. Participant 1, 4, and 5 gave the same ratings for each time.

### 5.3.3 Feelings on Wearing the Device

The way that participants felt wearing the device could depend on whether they were excited about the research aims of the project, what ADL they performed, how comfortable they felt, and the convenience of the trial. To capture how participants felt about the trial, device, and overall experience, the Participant Feedback Questionnaire used a numerical line scale to gather feedback. The participants provided a rating from 0.00 to 10.00. A rating of 0.00 would imply that the participant strongly disliked wearing the device all day, a rating of 5.00 means that the participant was indifferent about wearing the device all day, and a rating of 10.00 means they enjoyed wearing the device all day. The minimum rating was 2.00, and the maximum was 8.00. The average rating for participants feelings on wearing the device based of the 7 participants is 6.43 and has a standard deviation of 2.07, as displayed in Figure 5.16. This shows that most participants did not dislike the device and felt better than indifferent on wearing the device, but most did not enjoy wearing the device during their trial. To make the trial and device more enjoyable, the device could be made lighter and less bulky.

### 5.3.4 Ease of Donning and Doffing

The participants provided a rating of zero to ten in the Participant Feedback Questionnaire to describe how easy it is to put the device on and take it off. A rating of 0.00 would mean the device is very difficult to don and doff, a rating of 5.00 means it is not difficult nor easy to don and doff, and a rating of 10.00 means it is easy to don and doff.

For the first 2 trials, the sleeve and the glove were only connected by wires, and there was no fabric covering the wires between the glove and sleeve. This made the device more difficult to don and doff, because the participants needed to be more careful when removing the device. In the first 2 trials, wires became unsoldered between the glove and the sleeve from strain when donning and doffing. After the second trial, the glove and sleeve were connected with fabric to enclose the wires and protect the hardware. This prevented those wires from becoming unsoldered again in future trials, and prevented the wires from having direct contact with the skin.

The average rating for donning and doffing the device based on the 2 trials that occurred before the wires were enclosed by fabric to attach the glove and sleeve after one hour was 7.50 with a standard deviation of 0.71. After the device was modified to be one piece the average rating for ease of donning and doffing was 8.60 with a standard deviation of 0.89. The overall minimum rating is 7.00, and the maximum is 9.00. The average ease of donning and doffing of all 7 participants is 8.29 with a standard deviation of 0.95, as shown in Figure 5.16.

### 5.3.5 Convenience of Wearing the Device

The participants were asked to rate the convenience of wearing the device in the Participant Feedback Questionnaire. A rating of 0.00 implies that the device is very inconvenient to wear, a rating of 5.00 implies that the device is not convenient nor inconvenient, and a rating of 10.00 means that the device is convenient to wear. The minimum convenience rating was 3.00, and the maximum was 9.00. The average rating for convenience wearing the device based of all 7 participants is 6.57 with a standard deviation of 1.90 as shown Figure 5.16.

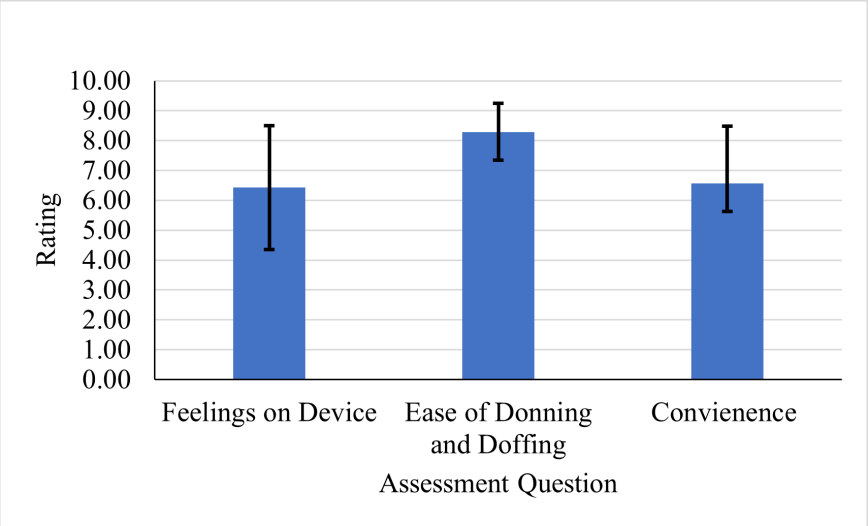


Figure 5.16: The average rating for the participants feeling on the device, how easy it is to don and doff, and the convenience of the device given after the trial was completed with standard deviation error bars shown in black.

## 5.4 Discussion

Analysis of voluntary motion signals in the frequency domain follows the same procedure that tremor analysis would follow in the future. The voluntary motion PSD and frequency values fall within the typical range for voluntary motion. For the index finger, the frequencies with the highest PSD were between 0 and 1.5 Hz during rest, 0 and 2.5 Hz during walking, and between 0 and 3 Hz during typing and computer use. The PSD data can show which frequencies have the highest power, indicating that most of the signals are around a specific frequency range. Previous research has shown that voluntary motion is generally less than 3.5 Hz, and tremor is between 3.5 and 15 Hz. When tremor is occurring, the frequency bands between 3.5 and 15 Hz have the highest PSD. When tremor is not active, the highest PSD is often seen at less than 3.5 Hz. Research has suggested a direct correlation between PSD and MDS-UPDRS Part 3 score. The higher PSD of a tremor, the more likely that individual would be given a higher MDS-UPDRS score by a neurologist [37]. The values extracted for frequency and PSD of an individual's tremor can be compared the the MDS-UPDRS assessment, to determine if the visual inspection performed by a neurologist accurately reflects the measured values during ADL in a home setting. In addition, the tremor features of individuals who do not visit a neurologist regularly can be obtained to lead

to a better understanding of an individual's PD tremor. This information can be shared with a neurologist to help provide better PD tremor management.

The data lost during the trials was mostly recovered by scanning and repairing the SD card and files using a command level utility and a recovery software. For the instance, when the SD card wires became unsoldered to the MCU during the first trial, corrections were made for the following trials to ensure that the wires did not get disconnected again, and this issue did not occur again.

The battery life was sufficient for every trial that occurred. The device had an average of 59% remaining after 48 hours for the 7 trials completed. This indicates that the battery supplied adequate power, and in future trials a battery pack with a lower capacity could be used to reduce the size and bulkiness of the device.

The ADL was helpful to identify what tasks were performed when certain data was recorded, allowing for task classification during data processing. The information in the Participant Feedback Questionnaire provides helpful insight to understand how the participants felt during the trial, and what could be improved in future studies. The comfort of the device, ability to perform ADL, feelings on the device, ease of don and doffing, and convenience could be improved in future devices by modifying the number of layers on the device, reducing the bulkiness of the battery pack, keeping it once piece, and having the battery in a region of the body that can bear more weight.

## 5.5 Conclusion

The device collected quantitative data in a home setting during 7 trials. The quantitative data collected are motion signals from the IMU sensors. The linear acceleration and angular velocity of the joints of focus were compared to give insight on the device functionality. In addition, the data was converted to the frequency domain using FFT to obtain the PSD values at certain frequencies, allowing for different length signals to be compared. Even though this was performed for voluntary motion signals, the same procedures could be used later for trials that capture tremor. The PSD at certain frequencies can help identify when tremor occurs, and can be correlated to an individual's

MDS-UPDRS score [44]. The ADL Log and the Participant Feedback Questionnaire collected qualitative data to capture what ADL were performed during the data collection and obtain feedback on the device comfort, ability to perform ADL wearing the device, how the participant felt about the device, ease of donning and doffing, and convenience of the device. The device has sufficient battery to last every trial, and data was captured over a 2 day period in a home setting.

# Chapter 6

# Conclusions

The device has been validated by performing trials on healthy participants with the same experimental procedure that can later be used to perform trials on individuals with PD tremor to capture helpful data on tremor behaviour and features in a home setting. Future research can improve the device comfort, trial experience, and device functionality. The developed device is the first to be able to collect motion data portably from all of the upper limb (excluding the shoulder), in a home setting over a 2 day period. The COVID-19 pandemic made recruitment of participants difficult, and individuals with PD were not able to be participants. In addition, the pandemic had an increased shipping time for hardware components and there was less stock of commercially available sensors and microcontrollers online.

## 6.1 Contributions

A wearable device that uses IMU sensors to collect upper-limb motion data and saving the data to an SD card was developed and tested on healthy participants. The glove and sleeve design allowed for adjusting the PCBs based on the distance between joints in the upper limb, Even though the comfort could be improved, the device was relatively light weight, and successfully collected data over 2 days. In addition, the battery life was sufficient for all 7 trials. Based on the research done, this is the only device that is portable and can collect data from 21 upper limb joints with the intention of use in a home setting. It is unique that the trial location is a

home setting, and is significant because it leads to the ability to capture more accurate ADL data, and understand voluntary motion during a participant's typical day. Most of the devices already developed in the literature capture data in a clinical or laboratory setting. In addition, the battery is capable of supplying power to the device for up to 3 days without recharging it. The COVID-19 pandemic changed how some health care services are delivered, shifting many in-person services to a virtual delivery method, leading to a need for ways to monitor health in a home setting. The same experimental procedure can be followed in the future to collect data on individuals that experience PD tremor. Since individuals with PD generally see a neurologist once per year, and the MDS-UPDRS Part 3 is conducted over a 15 minute period, a way to track and better understand tremor in a home setting where most ADL are performed can contribute to having a more accurate understanding of each participant's tremor and understanding whether tremor and specific ADL are correlated. By studying tremor in a home setting over 2 days, data on participant's individual tremor behaviour, how tremor impacts ADL, and how often an individual's tremor occurs in a typical day can be found. The collected tremor data could be used to better understand the characteristics of tremor such as PSD and frequency, how often tremor occurs for each participant, modelling, estimation, and control. This data could be later discussed with a neurologist to better manage PD. It is particularly helpful because having a way to capture tremor in a home setting during ADL could possibly lead to managing PD symptoms without medication or surgery.

## 6.2 Future Research

The work done on this project contributes greatly to being able to track voluntary motion, and eventually tremor in a home setting over a 2 day period. Even though this device met the research objectives, there are suggestions and improvements that could be implemented in future research and developed devices:

1. Less Bulky: When designing future devices, the bulkiness of the device could be reduced so that there are fewer components, lighter materials, and possibly more breathable fabrics. If the device had fewer components, it would take less time to assemble, would cost less to purchase, weigh less, and would be easier to configure. The battery pack selected could also

be smaller so that it is more comfortable for the participants to wear. The battery pack could be relocated so that it is not on the bicep or sitting over the sleeve of the device. Moving the battery pack to an area of the body that can bear more weight such as the legs or hips may feel easier to carry during ADL. In addition, the PCBs could be designed to have smaller dimensions, or be flexible so that the device is more compliant, and is less obtrusive.

2. Activity Logging: Based on the 7 trials performed, ADL were not logged an average of 13.93% of the time. Some participants struggled to update the ADL log for different ADL performed. For future studies, logging most ADL can be encouraged by prompting the participant to record an audio clip on a smart phone of what ADL they are performing at that time, if any. Explaining an ADL in an audio recording could be easier and faster than writing a description by hand.

3. Two MCU: If future designs save data to an SD card, it is recommended that the device has two separate MCUs. The MCU could not process the data at sampling frequency of 100 Hz, or every 10 ms due to the number of IMUs, and what was required to save the data to the SD card. When a sampling frequency of 100 Hz was tested, a significant amount of data was lost. In order to save the data to the SD card, the MCU needs to read the data, store it in memory, convert it to a string, and then save it to the CSV file. The highest sampling frequency that could reliably save the data was 28.57 Hz, or every 35 ms. If the data was saved as binary instead of strings, the sampling frequency might be able to be increased with a single MCU. However, it is suggested that there is one MCU responsible for reading the IMU data, and one for saving the data to the SD card because saving the data to the SD card is another likely cause of why a sampling frequency of 100 Hz was unsuccessful.

4. Different Method of Saving Trial Data: The current design saves data to an SD card, which causes certain obstacles that could be mitigated with a different storage method. Using an SD card requires more steps for the MCU compared to saving data by a serial connection or Bluetooth. The CSV file would not have to be open and closed, data would not be stored in a temporary buffer until it is time to write to the file, the sampling frequency could be increased, and no formatting of the SD card would be needed. Saving data by a serial

connection would require connection to a PC, so it could not be used in a portable device. Bluetooth also has challenges and can also result in data loss due to interference, but it could be considered in future designs by sending the data to a mobile app that receives and processes the data.

5. Trials to Capture PD Tremor: Since the device was validated on healthy participants, the next recommended step is to improve the device by making it more compact and comfortable, then performing trials on individuals with PD to capture tremor data. This will lead to a better understanding of how tremor impacts their daily life, and the impact tremor can have on ADL. Performing trials on individuals with PD can also lead to better management of PD and potentially better treatment. The data should be studies in the time and frequency domain, and the PSD values should be studied to identify tremor occurrence and understand the impact tremor has on individuals' ADL.

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# Appendix A

# Permissions and Approvals

The following approval is presented below:

- Ethics approval for Evaluation of a Wearable Sensing Device for Use in a Home Setting from Western University HSREB
- Letter of Information with the consent form for individuals that participate in trials
- Approval to use figure 2.3 from IEEE Sensors Journal, Vol. 18, No. 3
- Approval to use figure 2.4 from the IEEE Conference Proceedings 2016 IEEE-EMBS International Conference on Biomedical and Health Informatics
- Approval to use figure 3.3 from the IEEE Conference Proceedings: 2012 4th IEEE RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), 2012

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- Figure 3.5 From MDPI sensors vol. 19 No. 10 (open access)

Western Research

**Date:** 1 November 2021

**To:** Prof. Michael Naish

**Project ID:** 118552

**Study Title:** Evaluation of a Wearable Sensing Device for Use in a Home Setting

**Application Type:** HSREB Initial Application

**Review Type:** Full Board

**Meeting Date :** 24/Aug/2021 13:00

**Date Approval Issued:** 01/Nov/2021 07:28

**REB Approval Expiry Date:** 01/Nov/2022

---

Dear Prof. Michael Naish

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. **All other required institutional approvals and mandated training must also be obtained prior to the conduct of the study.**

**Documents Approved:**

| Document Name | Document Type | Document Date | Document Version |
|---|---|---|---|
| 1.10 Healthy Subject Research Plan (6) | Protocol | 27/Oct/2021 | 1 |
| 2.22 Participant Feedback Questionnaire (6) | Paper Survey | 27/Oct/2021 | 1 |
| 2.22 ADL Log (6) | Paper Survey | 27/Oct/2021 | 1 |
| Master Participant List(6) | Other Data Collection Instruments | 27/Oct/2021 | 1 |
| Participant Attribute Document(6) | Other Data Collection Instruments | 27/Oct/2021 | 1 |
| Ethics Poster (6) | Recruitment Materials | 27/Oct/2021 | 1 |
| 12.5 Email Recruitment (6) | Recruitment Materials | 27/Oct/2021 | 1 |
| 12.5 Email Recruitment (6) | Email Script | 27/Oct/2021 | 1 |
| Communication Scripts (6) | Email Script | 27/Oct/2021 | 1 |
| Ethics Poster (6) | Email Script | 27/Oct/2021 | 1 |
| 12.13 Letter of Information (6) | Written Consent/Assent | 27/Oct/2021 | 1 |

**Documents Acknowledged:**

| Document Name | Document Type | Document Date | Document Version |
|---|---|---|---|
| 14.10 WREM (6) | Study budget | 27/Oct/2021 | 1 |

No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB , except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.



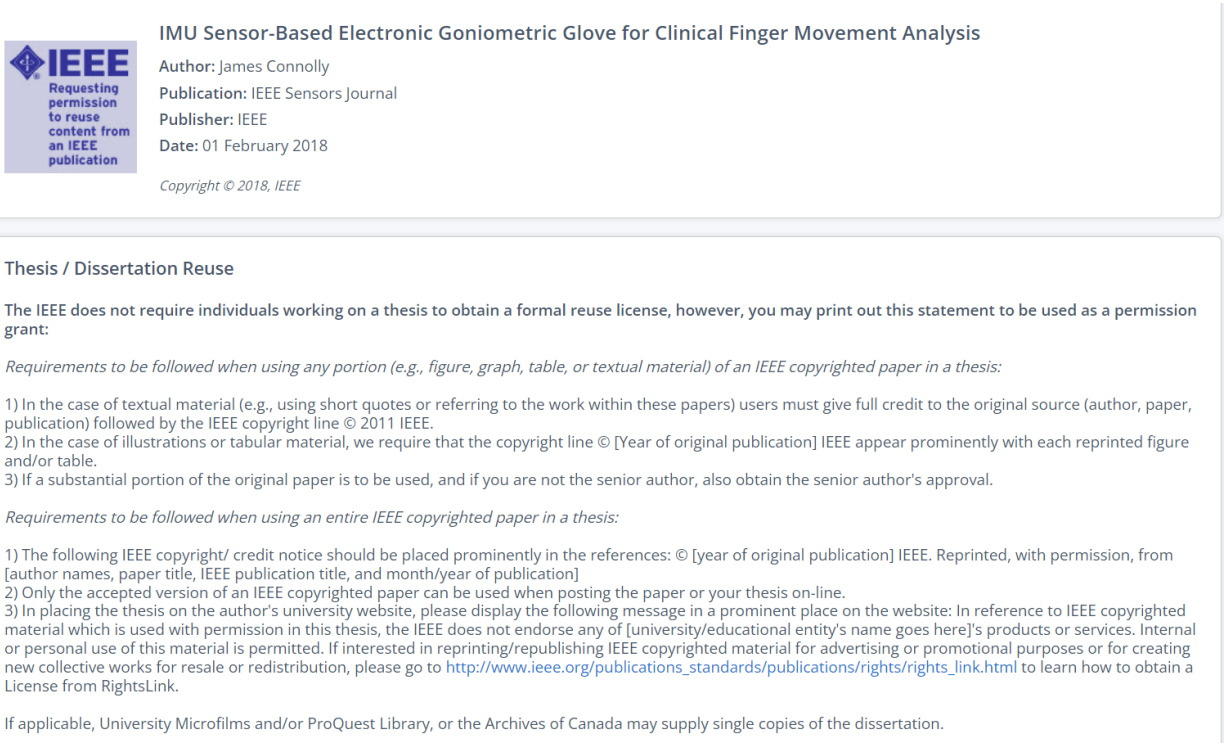
Figure A.1: WREM ethics approval page 1.

Please do not hesitate to contact us if you have any questions. Sincerely,

Ms. Nicola Geoghegan-Morphet , Ethics Officer on behalf of Dr. Emma Duerden, HSREB Vice-Chair

***Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).***

Figure A.2: WREM ethics approval Page 2.



IMU Sensor-Based Electronic Goniometric Glove for Clinical Finger Movement Analysis

**Author:** James Connolly
**Publication:** IEEE Sensors Journal
**Publisher:** IEEE
**Date:** 01 February 2018



Figure A.3: Approval to use images from IEEE Sensors Journal, Vol. 18, No. 3.


**The measurement and analysis of Parkinsonian hand tremor**

**Conference Proceedings:** 2016 IEEE-EMBS International Conference on Biomedical and Health Informatics (BHI)

**Author:** Y. Zhou

**Publisher:** IEEE

**Date:** February 2016



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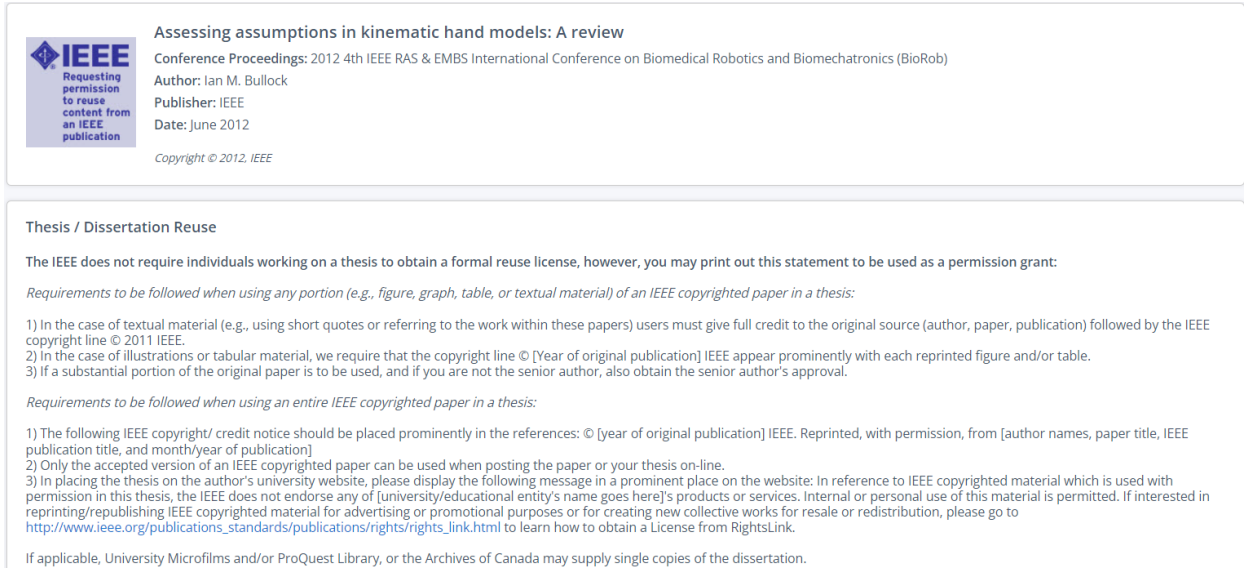
Figure A.4: Approval to use image from IEEE Conference Proceedings 2016 IEEE-EMBS International Conference on Biomedical and Health Informatics.



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**Assessing assumptions in kinematic hand models: A review**

**Conference Proceedings:** 2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)
**Author:** Ian M. Bullock
**Publisher:** IEEE
**Date:** June 2012





Figure A.5: Permission to use IEEE Conference Proceedings 2012 IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob).

# Appendix B

# Participant Trial Form: ADL Log

The following Appendix contains the first page of the ADL Log that individuals participating in trals were required to complete at least once every 2 hours.

Participant ID:

**Activities of Daily Living (ADL) Log**

Activities of Daily Living (ADL) are the tasks that occur in your everyday life. Some typical ADL include eating, getting dressed, getting into or out of a chair, walking, writing etc. Please log your activities or tasks being performed at least once every two hours while wearing the device. Please record as many of your ADL as possible while wearing the device. This log will be provided at the first visit to the WearMe Lab (ACEB 3410) and is to be filled out by hand. An electronic copy will also be sent to you following the first visit. If preferred, it can be completed electronically and emailed to after the trial.

| Activity Description | Start Time | End Time | Activity Duration |
|---|---|---|---|
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

Version date: 10/27/2021

Figure B.1: A Blank ADL Log.

# Appendix C

# Participant Trial Form: Participant Feedback Questionnaire

This section contains the Participant Feedback Questionnaire that participants completed to provide feedback on the overall trial experience after 1 hour into the trial, 24 hours into the trial, and at the end of their trial.

Participant ID:

**Participant Feedback Questionnaire**

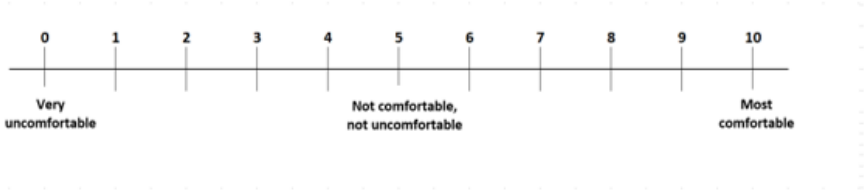
**Instructions for Participants:**

Please circle the number that you feel best reflects the comfort of the device and your ability to perform activities of daily living (ADL) while wearing the device. Activities of Daily Living (ADL) are the tasks that occur in your everyday life. Some typical ADL include eating, getting dressed, getting into or out of a chair, walking, writing etc. Please complete this **after 1 hour of wear, after 24 hours, and after your trial is finished.**

*Please note, if very uncomfortable, please remove the device. The device should not cause you this level of discomfort.*

**After 1 Hour of Wear**

**Comfort:**




**Ability to Perform ADL:**


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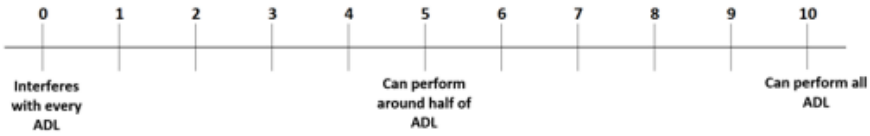
Figure C.1: A blank Participant Feedback Questionnaire page 1.

Participant ID:

**After 24 Hours of Wear**

**Comfort:**


**Ability to Perform ADL:**




Version date: 10/27/2021

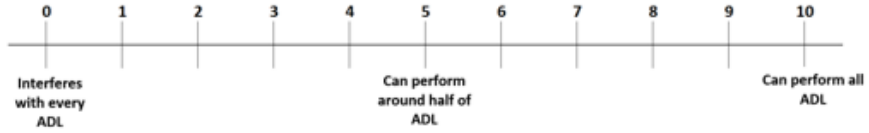
Figure C.2: A blank Participant Feedback Questionnaire page 2.

Participant ID:

**After 48 Hours of Wear**

**Comfort:**


**Ability to Perform ADL:**




**How did you feel about wearing the device for the duration of the trial?**


**Ease of Donning and Doffing:**

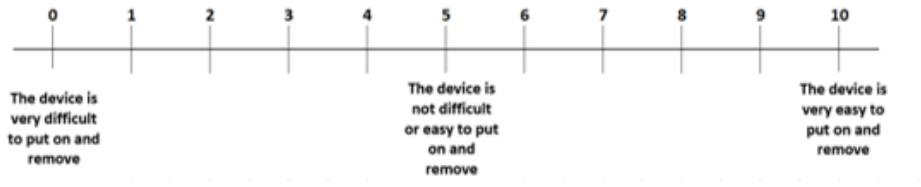



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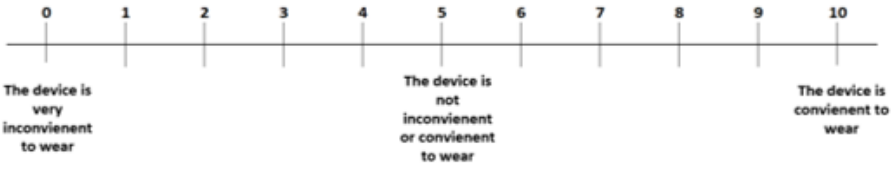
Figure C.3: A blank Participant Feedback Questionnaire page 3.

Participant ID:

**Convenience of Wearing the device:**




**Other Feedback:**

Please list any comments or feedback you have on the device or your experience with the trial in the space provided below:

Version date: 10/27/2021

Figure C.4: A blank Participant Feedback Questionnaire page 4.

# Appendix D

# Letter of Information

This section contains

- The first page of the Letter of Information that lists the researchers involved in this project.
- The consent form participants signed before the beginning of the trial.


**Letter of Information**

**Title: Evaluation of a Wearable Sensing Device for Use in a Home Setting.**

You are invited to participate in a research study to evaluate the performance of a wearable sensing glove to collect motion data from healthy participants. The results of this study will be used to validate the device and ensure that it can be used to collect tremor data from individuals with Parkinson's Disease (PD) in future studies. This study is being conducted by the following researchers:

**Dr. Michael Naish, Ph.D. (Principal Investigator)**
Associate Professor
Department of Mechanical and Materials Engineering, Department of Electrical and Computer Engineering, Faculty of Engineering
The University of Western Ontario
Email:
Tel:

**Jaspreet Kalsi (Graduate Student)**
MESc Candidate
Department of Biomedical Engineering, Faculty of Engineering
The University of Western Ontario
Email:
Tel:

**Dr. Ana Luisa Trejos, Ph.D. (Co-Investigator)**
Associate Professor
Department of Electrical and Computing Engineering, Faculty of Engineering
The University of Western Ontario
Email:
Tel:

**Dr. Yue Zhou, Ph.D.**
Postdoctoral Associate
Department of Biomedical Engineering, Faculty of Engineering
The University of Western Ontario
Email:
Tel:

Version date: 10/27/2021

Figure D.1: The first page of the Letter of Information lists the researchers associated with the research project.


**Consent Form**

**Title of Research:** Evaluation of a Wearable Sensing Glove for Use in a Home Setting

**Principal Investigator:** Dr. Michael Naish

**Collaborators:** Jaspreet Kalsi, Dr. Ana Luisa Trejos, and Dr. Yue Zhou

**For the Participant:**
This study has been explained to me and any questions I had have been answered. I know that I may leave the study at any time. I confirm that I do not meet any of the exclusion criteria. I agree to take part in this study.

If at any time I have further questions, problems or adverse events, I can contact Dr. Michael Naish, the Principal Investigator of the project, at ext. or Jaspreet Kalsi, a collaborator of the project, at

If I have any questions about my rights as a research participant or the conduct of this study, I may contact The Office of Research Ethics email:

By signing this consent form, I am indicating that I agree to participate in this study.

| | | |
|---|---|---|
| **Name of Participant (Please print)** | **Signature of Participant** | **Date** |
| **Name of Person Obtaining Informed Consent** | **Signature of Person Obtaining Informed Consent** | **Date:** |

Version date: 10/27/2021

Figure D.2: A Blank copy of the consent form each participant signed after reading the LOI to take part in trials

# Appendix E

# Linear Acceleration and Angular Velocity Data

This section contains

- The linear acceleration data for each IMU sensor.
- The angular velocity data for each IMU sensor.

Table E.1: Linear acceleration values in g for the thumb IMUs. IMU 2 is above the MCP joint and IMU 3 is below it.

| | **IMU 2** | **IMU 3** |
|---|---|---|
| **A min** | 0.002 | 0.000 |
| **A max** | 3.890 | 3.230 |
| **A Avg** | 1.015 | 0.045 |

Table E.2: Linear acceleration values in g for the index finger IMUs. IMU 4 is above the DIP joint, IMU 5 is below the DIP joint and above the PIP joint, IMU 6 is below the PIP joint and above the MCP joint, and IMU 7 is below the MCP joint.

| | **IMU** 4 | **IMU 5** | **IMU 6** | **IMU 7** |
|---|---|---|---|---|
| **A min** | 0.000 | 0.000 | 0.000 | 0.000 |
| **A max** | 4.100 | 3.210 | 2.890 | 2.870 |
| **A avg** | 0.055 | 0.474 | 0.053 | 0.049 |

Table E.3: Linear acceleration values in g for the middle finger IMUs. IMU 8 is above the DIP joint, IMU 9 is below the DIP joint and above the PIP joint, IMU 10 is below the PIP joint and above the MCP joint, and IMU 11 is below the MCP joint.

| | **IMU 8** | **IMU 9** | **IMU 10** | **IMU 11** |
|---|---|---|---|---|
| **A min** | 0.000 | 0.000 | 0.000 | 0.000 |
| **A max** | 2.156 | 3.456 | 2.566 | 3.123 |
| **A Avg** | 0.055 | 0.057 | 0.055 | 0.050 |

Table E.4: Linear acceleration values in g for the ring finger IMUs. IMU 12 is above the DIP joint, IMU 13 is below the DIP joint and above the PIP joint, IMU 14 is below the PIP joint and above the MCP joint, and IMU 15 is below the MCP joint.

| | **IMU 12** | **IMU 13** | **IMU 14** | **IMU 15** |
|---|---|---|---|---|
| **A min** | 0.000 | 0.000 | 0.000 | 0.000 |
| **A max** | 4.120 | 3.129 | 3.012 | 3.098 |
| **A Avg** | 0.060 | 0.058 | 0.051 | 0.114 |

Table E.5: Linear acceleration values in g for the pinky finger IMUs. The linear acceleration for the pinky finger is shown in Table 5.5. IMU 16 is above the DIP joint, IMU 17 is below the DIP joint and above the PIP joint, IMU 18 is below the PIP joint and above the MCP joint and IMU 19 is below the MCP joint.

| | **IMU 16** | **IMU 17** | **IMU 18** | **IMU 19** |
|---|---|---|---|---|
| **A max** | 0.000 | 0.000 | 0.000 | 0.000 |
| **A min** | 3.123 | 3.096 | 4.130 | 3.452 |
| **A Avg** | 0.068 | 0.047 | 0.049 | 0.047 |

Table E.6: Linear acceleration values in g for the elbow IMUs. IMU 20 is above the elbow joint and IMU 21 is below the elbow joint. The linear acceleration values for the wrist is shown in Table 5.7. IMU 22 is above the wrist joint and IMU 23 is below the wrist joint.

| | **IMU 20** | **IMU 21** |
|---|---|---|
| **A min** | 0.000 | 0.000 |
| **A max** | 3.200 | 3.019 |
| **A avg** | 0.026 | 0.038 |

Table E.7: Linear acceleration values in g for the wrist IMUs. IMU 22 is below the wrist and IMU 23 is above the wrist.

| | **IMU 22** | **IMU 23** |
|---|---|---|
| **A min** | 0.000 | 0.000 |
| **A max** | 4.120 | 3.103 |
| **A Avg** | 0.047 | 0.146 |

Table E.8: Angular velocity values for the thumb MCP joint, the index dip joint, the index PIP joint, and the index MCP joint

| | **Thumb** | **Index DIP** | **Index PIP** | **Index MCP** |
|---|---|---|---|---|
| **Gx min** | -76.713 | -707.761 | -728.060 | -481.813 |
| **Gx max** | 16.675 | 890.636 | 638.196 | 931.156 |
| **Gx avg** | 0.455 | 8.568 | 7.197 | -315.964 |
| **Gy min** | -18.048 | -393.663 | -552.639 | -501.565 |
| **Gy max** | -78.773 | 832.119 | 612.270 | 964.493 |
| **Gy Avg** | -0.712 | 2.709 | 0.689 | -532.307 |
| **Gz min** | 105.229 | -788.884 | -893.837 | -369.101 |
| **Gz max** | -52.231 | 984.030 | 680.887 | 910.479 |
| **Gz avg** | -0.317 | -4.359 | -6.280 | -253.093 |

Table E.9: Angular velocity values for the middle finger DIP, PIP and MCP joint.

| | **Middle DIP** | **Middle PIP** | **Middle MCP** |
|---|---|---|---|
| **Gx min** | -502.063 | -523.504 | -481.764 |
| **Gx max** | 310.470 | 1201.106 | 562.910 |
| **Gx avg** | -2.489 | 6.079 | -1.118 |
| **Gy min** | -660.944 | -1054.607 | -501.969 |
| **Gy max** | 256.269 | 397.433 | 476.117 |
| **Gy Avg** | -2.991 | -0.282 | -0.971 |
| **Gz min** | -475.271 | -1264.156 | -370.319 |
| **Gz max** | 280.911 | 1264.941 | 584.054 |
| **Gz avg** | -1.979 | -6.338 | -0.058 |

Table E.10: Angular velocity values for the ring finger DIP, PIP and MCP joint.

| | **Ring DIP** | **Ring PIP** | **Ring MCP** |
|---|---|---|---|
| **Gx min** | -234.12 | -357.695 | -328.657 |
| **Gx max** | 321.905 | 297.575 | 144.543 |
| **Gx avg** | -0.899 | 0.312 | 0.761 |
| **Gy min** | 83.206 | -389.835 | -623.863 |
| **Gy max** | -75.220 | 337.161 | 463.597 |
| **Gy Avg** | -2.502 | 1.101 | -2.398 |
| **Gz min** | -44.652 | -319.990 | -428.676 |
| **Gz max** | 49.638 | 310.356 | 190.53 |
| **Gz avg** | -0.601 | 0.072 | -0.296 |

Table E.11: Angular velocity values for the pinky finger DIP, PIP, and MCP joint.

| | **Pinky DIP** | **Pinky PIP** | **Pinky MCP** |
|---|---|---|---|
| **Gx min** | -203.34 | -142.12 | -11.264 |
| **Gx max** | -8.198 | -119.878 | -4.012 |
| **Gx avg** | 0.281 | 0.151 | 0.269 |
| **Gy min** | -48.348 | 244.924 | 33.214 |
| **Gy max** | 36.144 | 24.574 | -4.542 |
| **Gy Avg** | 1.092 | -1.741 | 1.081 |
| **Gz min** | -92.34 | -7.488 | -21.684 |
| **Gz max** | 302.21 | 456.21 | 456.42 |
| **Gz avg** | -0.120 | -0.094 | -0.425 |

Table E.12: Angular velocity values for the radiocarpal (wrist), CMC, and elbow joint.

| | **Radiocarpal Joint** | **CMC Joint** | **Elbow Joint** |
|---|---|---|---|
| **Gx min** | -232.624 | -238.786 | -96.532 |
| **Gx max** | 405.420 | 570.440 | 211.604 |
| **Gx avg** | 0.168 | 0.578 | 0.713 |
| **Gy min** | -127.358 | -170.550 | 89.054 |
| **Gy max** | 107.936 | 312.672 | 40.266 |
| **Gy Avg** | 1.715 | 0.126 | -0.894 |
| **Gz min** | -321.590 | -526.784 | -108.900 |
| **Gz max** | 293.112 | 493.628 | 128.262 |
| **Gz avg** | 0.186 | 0.842 | 0.319 |

**Curriculum Vitae**

| | |
|---|---|
| **Name:** | Jaspreet K. Kalsi |
| **Post-secondary Education and Degrees:** | University of Windsor<br>Windsor, Ontario, Canada<br>2016–2020 B.A.Sc.,<br>Industrial and Systems Engineering (minor in Business Administration)<br><br>Western University<br>London, Ontario, Canada<br>2020–2022 M.E.Sc.,<br>Biomedical Engineering (Mechatronics Stream) |
| **Related Work Experience:** | Teaching Assistant<br>*GENG 4000 – Engineering Technical Communications*<br>University of Windsor<br>2018–2020<br><br>Teaching Assistant<br>*ES 1050 – Foundations of Engineering Practice*<br>Western University<br>2020–2022<br><br>Research Assistant<br>Western University<br>2020–2022 |