1. Introduction

1.1. Motivation and objectives

There are basically two categories of human motions: voluntary and involuntary. Voluntary motion is the motion involving intention while involuntary motion is unintentional. An example of involuntary motion is the tiny vibration of the hand when one is trying to hold his/her hand still because of the feedback mechanisms of the human body. However, the involuntary motion is significant for those suffering from neurological disorder like Parkinson's disease, which makes the patients difficult to write, eat or hold something, and hence social embarrassment. Tremor is a rhythmic, involuntary muscular oscillation at a relative fixed frequency and amplitude, which is also a symptom of several kinds of neurological conditions or neurological disorders caused by aging. Tremor can affect different parts of the body such as head, tongue, legs, and hands. Most common tremors are at the hands. There are two primary categories of tremors: resting and action tremor. Resting or static tremor appears when the target muscle or muscle group is at rest, which is the most commonly associated with Parkinson's disease. In contrast, action tremor appears when the target muscle or muscle group is in use. The tremor frequency is typically in the range of 3 – 12 Hz, where resting tremor is observed within the range 3 – 7 Hz (up to 75% of patients with Parkinson's disease) and action tremor is observed within the range 5 – 12 Hz (around 65% of patients with Parkinson's disease) [1-8], which was summarized in the table 1.1.

Tremor Type	Frequency	Affected Limbs
Essential (postural & kinetic)	3 – 12 Hz	Finger: Abduction-adduction Wrist: Flexion-extension Forearm: Pronation-supination
Parkinsonian (rest)	3 – 6 Hz	Finger: Flexion-extension Wrist: Flexion-extension Forearm: Pronation-supination
Cerebellar (intention & kinetic)	2 – 4 Hz	Wrist: Flexion-extension Proximal Muscles

Table 1.1 A brief summary of different type of tremor.

Currently the clinical treatments available for tremor are medication, psychotherapy, neurosurgery and deep brain stimulation. However, these treatments still have some side effects. Pharmacological drugs will not be effective to the tremor suppression over time and may cause fatigue, sleepy, nausea, poor vision and muscle paralysis. Psychotherapy is sometimes effective to patients. Neurosurgery requires high surgical precision that is in high risk to patient. Deep brain stimulation reduces the tremor by stimulating certain brain areas but it is just effective to some patients and may cause some side effects such as disturbances in behavior and cognition and cerebral hemorrhage. [9, 10] Therefore, none of these treatments can guarantee a permanent solution to manage tremor effectively and further research and development of new alternative approaches to reduce the tremors is needed. It was found that a less invasive approach like biomedical devices actuated the human body externally might be the alternative to attenuate the tremor. [11, 12] Several suppression devices are suggested and developed, for example, Neater Eater [13], MIT Damped Joystick [14-17], “controlled Energy-Dissipation Orthosis” (CEDO) and the second generation of CEDO “Modulated Energy Dissipation Manipulator” (MEDM) [18-21], ”Viscous Beam” [22] and its similar design with magneto-rheological fluids [23], “wearable orthosis for tremor assessment and suppression" (WOTAS) [24-28], a glove with piezoelectric materials [29, 30], and those orthotics with conducting polymer actuators [31], magneto-rheological dampers [32], electromagnetic friction brake [33] or functional electrical stimulation (FES) [34-37]. However, many of these devices are bulky, heavy and in low power capacity for a portable and wearable device for patients. Liftware, a stabilizing handheld device to help eating, produced by Lift Lab and Steady Write® Writing Instrument are currently two of the most successful commercial products designed for tremor suffering patients. However, all these products are only dealing with one specific area like eating or writing.

Given the above limitations and side effects of those current developments, an effective, multifunctional, light, portable, minimal invasive tremor suppression orthosis is remained in high necessity. In this thesis, an exosuit is proposed to be the alternative for the treatment of tremor suppression in order to provide an effective, light, portable, minimal invasive tremor suppression orthotic approach for Parkinson's tremor or Essential tremor suppression. Since most of the affected limbs will be occurred in flexion-extension at wrist joint and pronation-supination of forearm for different type of tremors, the wearable device will focus on suppressing the tremor in flexion-extension at wrist joint and pronation-supination of forearm. By using 3D printed materials, the lightweight robot can provide sufficient support for dampening tremor. In addition, inertial measurement units (accelerometer and gyroscope) and electromyography (EMG) sensors are used to evaluate the tremor suppression function of the device and potential used to be a real time monitoring system to have machine learning classification of the daily life activities in order to cut off the power to the device when the suppression is not necessary.

1.2. Architecture of project development

The project was done following a development architecture shown in figure 1.1. Before starting designing the tremor suppression system, the tremor was studied and analyzed by using different decomposition methods to extract the simulated tremor motion from the raw data signal that collected from six healthy volunteers following an experimental protocol. Then the research work was separated into two main parts: cognitive human-robot interaction and physical human-robot interaction.

The cognitive interaction will investigate the interactions between human and robot and develop a control system logic that will respond to the tremor motion and voluntary motion. Physical interaction will focus on the development of the wearable exoskeleton device interacting with the hand and arm. During the research development at these two stages, the design process involved both directions to and fro between the software and hardware development since the control system may cause the change in the structural design of the device, vice versa.

At last, both control system and wearable device were tested by three volunteers for the validation of whole device and getting feedback of end users' experience on using the device. The validation, evaluation of the system and the feedback from end users are very important to the research process, as there are some new knowledge being discovered to improve the design of the system logic and the hardware device.

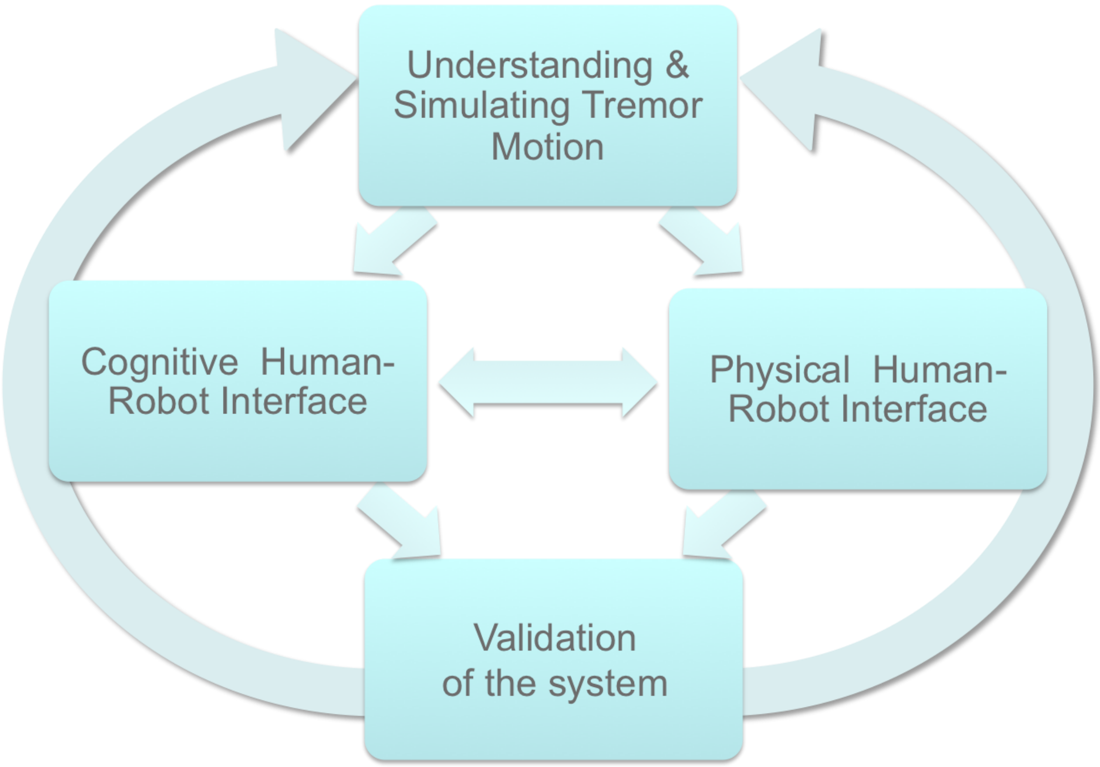


Figure 1.1 The architecture of project development.

1.3. Contributions of this thesis and publications

Chapter 2 will describe the review of current research and development of exoskeletons and soft exosuits, their advantages and their limitations. **Chapter 3** will introduce the application of sensor fusion using the layered Body Sensor Network (BSN) device for wireless motion capture system on the tremor motion identification. **Chapter 4** then describes the mechanical design, mechatronics and the control strategies of the proposed tremor suppression system. The tremor suppression performance of the system is being evaluated and discussed. **Chapter 5** will describe the work using machine-learning classification to classify the activities of daily life so as to provide the guideline for the prediction of the user behavior by the system. **Chapter 6** concludes the thesis and elaborates the potential research plan in future.

1.3.1. Publications and future publications

1) Denis Huen, Jindong Liu, and Benny Lo, “Assistive Wearable Robotics: Healthcare’s New Clothes”, IEEE Life Science Column, May 2015 (**published**)

2. Assistive wearable robotic: exoskeleton review

2.1. State of art

Exoskeletons and soft exosuits, the large family of the wearable robot, are robotic systems and devices that can let human beings wear in parallel to the human body in order to enhance their performance like strength or restore locomotion, while the other portion of the family is active prostheses that are in series to the human body by replacing the missing limbs. The development principle is basically separated into two directions: 1, to increase strength and load capacity of the human body; 2, to restore the locomotion and enhance the strength of those are the disabled or injured people by several diseases. The initiation of the development can be traced back to the years 1960s for the military, non-military and medical purpose, which are the "Hardiman" developed by General Electric company for the commission from the joint US Army/Navy initiation [38-40] and the researches of biped locomotion by Yugoslavia at el. [41] respectively. However, due to technological limitation at that time, those developments were not turned into production. Nowadays, high-speed signal processor, advanced position and force sensors and precise actuator control system are sufficiently good enough to contribute real benefits to the society, although the power sources and actuators are still being the main challenge to provide sufficient energy to operate the device for more than few hours, high power density actuation and precise motion. Also, the materials used for building the main structure and the safety issue are needed to be considered in order to construct a more practical exoskeleton.

2.2. Military application

As wearable robotics can provide high loading capacity and enhance the strength of the human body, there are many research projects launched by Europe, Asia and U.S. Defense Advanced Research Projects Agency (DARPA) such as "Exoskeletons for Human Performance Augmentation", "Revolutionizing Prosthetics Program" and "Warrior Web Program". DARPA launched the seven-year programme "Exoskeletons for Human Performance Augmentation" with 75 million dollars investment in 2000, and therefore 14 design proposals of exoskeleton were received and one of them, Sarcos (part of Raytheon now), was selected to build the first full body exoskeleton prototype "XOS" under the aim of "soldier of tomorrow". "XOS" in the weight of 68 kg uses an internal combustion engine to power the hydraulic actuators and controlled by detecting the wearer's motion that can let the wearer to lift 91 kg object, while "XOS 2" was developed in 2010, which was lighter, stronger, faster and more efficient than "XOS". However, the "XOS 2" can operate for about 40 minutes with battery power supply only and the development of it was not funded by DARPA. [39, 40, 42]

Another DARPA funded research held by Biomechatronics Group in Media Lab at Massachusetts Institute of Technology (MIT) is to develop exoskeletons to reduce the burden on soldiers and those carrying heavy objects in 2006. The exoskeleton prototype is a 11.8kg weight lower limb device powered by 48V batteries, which can reduce the burden loading on the back of the wearer. However, there are some tests showing that the oxygen consumption is 10 percent more than the person taking the same object without wearing it and that is caused by the interference between human and the device since the exoskeleton is not likely to mimic the movement of human body well. [43-47]

Berkeley Lower Extremity Exoskeleton (BLEEX) is the world's first load-carrying lower extremity exoskeleton developed by the University of California at Berkeley in 2005 with the grant from DARPA when it began the research on the feasibility of exoskeletons for human's performance since 2000. The exoskeleton uses hydraulic actuators and more than 40 sensors to form a local network mimicking the human nervous system of human. Apart from military use, it is also expended into health and medical application. [48-55]

Berkeley Bionics (Ekso Bionics now) originally developed the "Human Universal Load Carrier" (HULC) under the military development of Lockheed Martin company starting from 2009. HULC is a lithium polymer battery powered, titanium structured and hydraulically actuated lower-body exoskeleton in the weight of 24 kg without the batteries, which can let wearer carry 90 kg object for up to 20 km at a speed of 4 km/hour after a single battery charging. It shows that the wearer consumes 5 – 12 percent less oxygen during walking at 0.89 meter/second and around 15 percent less when carrying 36.7kg object at the same speed, which is good enough for the application in long-duration military mission. Recently, U.S. Army Natick Soldier Research Development and Engineering Centre in Massachusetts evaluated the newer version of HULC with longer battery power time and optimal software operation system. [39, 40, 56]

In 2001, a French company called RB3D was founded and started developing exoskeletons for different fields of application. As the partnership with the Directorate General for Armaments, RB3D, developed the first prototype "Hercule" and demonstrated it successfully in 2011, allows wearer to carry 20 kg object for each arm. Its batteries can provide the operation time up to 20 km at a speed of 4 km/hour. Recently, "Hercule V3", a lithium ion battery powered, lower-body exoskeleton was launched for its application in the area like manufacturing industry and on the construction sites respectively. [39, 40]

2.3. Non-military application

Exoskeleton also shows a great potential application in non-military fields such as manufacturing, construction, fire fighting, disaster response, rescue operation and other field requiring manual workers.

Apart from “Hercule V3” developed by RB3D, there are several other exoskeleton researches being commercialized. The most famous one is the “Hybrid Assistive Limb” (HAL) exoskeleton by Cyberdyne, Inc., a spin-out company from the Tsukuba University, which was founded in 2004 for commercializing the research work of the cybernetics research group leaded by Yoshiyuki Sankai, a professor from the System and Information Engineering at the Tsukuba University. The HAL exoskeleton is developed with the aim for physical therapy, assisting the disabled, enhancing the load carrying capacity for workers and disaster and emergency rescues. It weights 23 kg and is powered by a 100V battery with actuation by electric motors that can operate for around 3 hours. The control system of the suit initiates motion by detecting the myoelectric signals, voltages related to the brain signals being sent to the muscles, via sensors attached on the skin of the wearer, and therefore it can respond fast to the change of the intention of those people who are with spinal cord injuries or paralyzed limbs. Cyberdyne was certificated by Underwriters Laboratories to ISO 13485 (the international quality standard for medical devices) in December 2012, received a global safety certificate in February 2013 and an European community (EC) certificate in August of the same year, which makes HAL be the first powered exoskeleton to have these certificates. [57-62]

“MS-02 PowerLoader”, a bulky heavy full body exoskeleton actuating with 22 servomotors that the wearer can able to lift 50 kg object for each arm, which was developed by ActiveLink, part of Panasonic, found in 2003. The system of the exoskeleton is “Direct Force Feedback System” that measures the magnitude and direction of the force exerted by foot with a 6-axis force sensor and hence it can follow the motion of the wearer well. “PLL-04 PowerLoader Lite” (Ninja) is then developed recently and is a lower limb exoskeleton, a smaller version of “MS-02 PowerLoader” powered by lithium-ion batteries in the weight of about 15 kg. In cooperation with Mitsubishi Heavy Industries and Japan Atomic Power, the exoskeleton is applied for nuclear industry that can help the clean up work in the Fukushima Daiichi nuclear power plant. [39, 40]

A full-body exoskeleton for assisting workers to manipulate and carry heavy objects in ship construction industry is developed by Korean Daewoo Shipbuilding and Marine Engineering. It weighs 28 kg, is made from carbon fiber, aluminum alloys and steel and actuates with electric motors or hydraulics that enable wearer to lift 30 kg object. The prototype with electric motors can operate up to 3 hours with the power from the batteries. [40]

2.4. Healthcare application: rehabilitation

Over 270,000 people is estimated to have long term spinal cord injuries in the USA and 20 percent of that will suffer from full paraplegia in 2012, while 185 million people is estimated to use wheelchair daily over the world. Also, only 4.9 percent of the world’s population was 65 or above years old, however, it becomes 20 percent nowadays and is forecast to be over 34 percent in 2050. And therefore exoskeletons can be applied to assist the disabled, injured and elderly to retain their certain independence and keep their active living style. Apart from providing force to assist wearer, exoskeleton can also provide force to resist and constraint for controlling the wearer's abnormal movements like tremor caused by neural disorder diseases. The systems can be divided into three groups: upper limb, lower limb and full body.

2.4.1. Lower Limb

"eLEGS" developed by Katherine et al. and commercialized by Ekso Bionics in 2010 is a trunk-hip-knee-ankle-foot multi-joint exoskeleton allowing patient to walk, stand up and sit down. The movement of the exoskeleton is triggered by the swinging motion of the patient's arms and the crutches, the weight shifting of the patient's body and the heel striking. [56, 63]

"ReWalk" developed by Dr Amit Goffer at the Israel's Institute of Technology and commercialized by ReWalk Robotics, formerly ARGO Medical Technologies found in 2001, is a light, wearable exoskeleton consisting of a metal frame that supports the legs and some parts of the upper body, DC motors at hip, knee and ankle joints, rechargeable batteries, sensors and computer control system. Although the whole system weighs 21 kg, it supports its own weight and therefore wearer will only feel the part of the weight that is about 2.3 kg from the backpack. The wearer needs crutches for additional stability when standing, walking and standing up from a chair. A wireless remote control is attached on the wrist, by which the wearer can activate and control the exoskeleton. [39, 62, 64, 65]

"REX Rehab" and "REX Personal" developed by Rex Bionics (acquired by Union MedTech plc. In 2014) are robotic exoskeleton legs with strong hip frame that enable wearer to stand up and walk, especially for patient having high level of mobility impairment, without using the crutches or walking frame to provide walking stability. The exoskeleton is actuated by DC motors, controlled by a keypad and joystick and has an interchangeable lithium-ion battery pack for about 2 hours operation. [66]

“Vanderbilt lower-limb orthosis” developed by Quintero et al. has a modular design structure only consisting of three main modular parts: left and right lower limb frames, and a hip orthosis with a mechanical and electrical control system. Wearer also needs crutches for walking stability and safety. The knee joints are equipped with brakes that lock normally during power failure. The gait training movement of the exoskeleton is preprogrammed based on the normal walking trajectory from a healthy subject wearing the exoskeleton. [39, 67]

“AUSTIN” exoskeleton developed by Wayne Yi-Wei Tung et al. in University of California Berkeley, Berkeley, has a novel design that uses only 1 actuator for each exoskeleton leg to actuate the exoskeleton minimally. The actuator powers the motion at the hip joint while the motion for knee joints is powered by the proposed coupling mechanism transmitting power through the wires from hip. [68]

HAL exoskeleton by Cyberdyne, Inc. is a wearable exoskeleton built in several versions including a full body version and two-legged version, which detects the EMG signals to trigger the assistive support according to the cybernic voluntary control system. The version 5 of HAL (HAL5) is currently undergoing clinical tests. Single leg version of HAL is also developed for supporting people with hemiplegia to walk. [57-62]

“Bodyweight Support Assist” and “Walking Assist Device” are products developed by Honda Motor Company that has been working on lower limb exoskeletons at its Fundamental Technology Research Centre in Wako, Saitama since the late 1990s. “Walking Assist Device”, weighs 6.5 kg, is launched in late 2008 and aimed at those with weakened leg muscles. It is actuated by two electric motors powered by a lithium-ion battery for about 2 hours as the wearer is walking slower than 4.5 km/h. [69, 70]

“Active Knee Rehabilitation Orthotic Device” (AKROD) is developed by Brain Weinberg et al. in 2007 for correcting the hyperextension of knee joint and the stiff-legged gait of patients after stroke. An electro-rheological fluid (ERF) is applied in this exoskeleton to generate resistant forces to prevent the buckling of knee joint for motor recovery. [71, 72]

Knee exoskeleton developed by Pieter Beyl et al. in 2008 consists of 4 frame linkages and a counter pair of 2 pleated pneumatic artificial muscles (PPAM) that can be actuated independently to contract axially and expend radially. Since the exoskeleton uses the optimal hardware design method, the data from clinical gait analysis (CGA) is used to make sure that the design specification fulfils the design requirement. [73]

“AlterG Bionic Leg” developed by Christopher et al. in 2012 and commercialized by Tibion company is a single-joint knee wearable exoskeleton or robotic knee orthosis (RKO), which uses plantar pressure sensor to detect the gait cycle and angle sensor and torque sensor to measure the angle of knee joint and the torque on it respectively. These signals from sensors can determine whether the knee joint of the exoskeleton is needed to be in assistance mode such as the state from stand to sit, free swing, climbing up stairs and flexion-extension of knee. [74]

For ankle rehabilitation, two notable examples are the “MIT active ankle-foot orthosis” (MIT-AFOs) and the magneto-rheological fluid (MR) brake AFO. MIT-AFOs developed by MIT in 2008 utilizes a series elastic actuator (SEA) connected to the AFO, which the SEA can be controlled to change the flexion or extension of the ankle. [43, 75] MR brake AFO, however, uses a shear-type compact MR brake for the actuation of the exoskeleton. The MR fluid inside several layers of disks can be controlled by changing the magnetic flux across them and hence the resistive torque can be applied onto the ankle to maintain the dorsiflexion and prevent dropping the foot when the leg is swinging. [76]

2.4.2. Upper Limb Exoskeletons

"Motorized Upper Limb Orthotic System" (MULOS) developed by the University of Newcastle under the funding from the Technology Initiative for Disabled and Elderly (TIDE) program of the Commission of European Communities in 1997 allows 5 degrees of freedom including 3 degrees of freedom at the shoulder joint, 1 degree of freedom at elbow joint for flexion or extension, 1 degree of freedom at forearm for pronation or supination, which is powered by cable-driven actuation mechanism with electric motors and hydraulic actuators. The shoulder joint of it uses intersecting axes structures to mimic the spherical joint with a centre coincident with the shoulder of the wearer. [77]

"Soft-actuated exoskeleton" developed by the University of Salford in 2003 consists of 7 degrees of freedom including 3 degrees of freedom at the shoulder joint, 1 degree of freedom at elbow joint for flexion or extension, 1 degree of freedom at forearm for pronation or supination, and 2 degree of freedom at wrist joint for flexion or extension and radial or ulnar deviation. Exceptionally, it uses strain gauge instead of force sensor to measure the movement and pneumatic muscle actuators instead of electric motors to actuate the exoskeleton. However, it requires bulky pneumatic system for experimental setup to operate the exoskeleton. It weighs 2.0 kg for the exoskeleton structure excluding the other part of the pneumatic system. [78]

"CADEN-7" upper limb exoskeleton developed by the University of Washington in 2007 is 9.3 kg excluding the weight of actuators, which allows 7 degrees of freedom (3 degrees of freedom at the shoulder joint, 1 degree of freedom at elbow joint for flexion or extension, 1 degree of freedom at forearm for pronation or supination, and 2 degree of freedom at wrist joint for flexion or extension and radial or ulnar deviation) to assist wearer by using cable-driven actuators mechanism to transmit power to the joints with the adjustable joint alignment mechanism between the wearer and exoskeleton. The advantage of using cable-driven actuation is the low reflected inertia at the end-effector. Apart from using force sensor, electromyography (EMG) signal is measured and used for the control system. [79]

"Dampace", stands for Damped Space or Pace, a dynamic force-coordinator trainer developed by Stienen et al. in 2007. It uses hydraulic disk brakes to control braking on the 3 rotational axes of the shoulder and 1 axis of the elbow, which is safe and encouraging patient to participate in movement actively, however, it can't provide an assistive force to the patient and create all kinds of different virtual environments. The axes of exoskeleton is not needed to be aligned with the axes of the human shoulder and elbow since it allows some additional mobility at the shoulder and elbow joints like 2 translational degrees of freedom at the shoulder joint. In order to motivate the patient to move actively, the system is also linked to a game therapy. [80, 81]

"L-EXOS", stands for light exoskeleton, a force feedback robotic exoskeleton for the right arm is developed by Frisoli et al. in 2007 allows 5 degrees of freedom including 3 degrees of freedom at the shoulder joint, 1 degree of freedom at elbow joint for flexion or extension, 1 degree of freedom at forearm for pronation or supination. The first four joints are actuated by DC servomotors with cable-driven mechanism and equipped with sensors while the last one is only equipped by a sensor. Since it is using cable to transmit forces to the joints, the exoskeleton is light with highly backdrivability. The whole system is linked with video projection system to provide the virtual environment for patients to perform rehabilitation task exercises actively and to be passively assisted by the exoskeleton when the patient can't perform the task. [82, 83]

"ARMin" project initiated by Nef et al. at the Swiss Federal Institute of Technology in Zurich in 2003 allows 4 degrees of freedom at shoulder joint and elbow joint for "ARMin I" prototype, 6 degrees of freedom for "ARMin II" prototype including 3 degrees of freedom at shoulder joint for horizontal, vertical and internal or external rotation, 1 degree of freedom at elbow joint for flexion or extension, 1 degree of freedom at forearm for pronation or supination and 1 degree of freedom at wrist joint for flexion or extension. "ARMin III" developed in 2009 is the improved version for ARMin II in the complexity, user operation, robustness and reliability. The actuation is powered by electric motors with 2 sensors in each motor for measuring the redundant. ARMin is considered to be a semi-exoskeleton according to its structure with an aluminum frame fixed on the wall or mounted on other object. It provides a set of neurological rehabilitation exercises with game therapy such as picking and placing objects, and catching a ball in virtual reality. ARM III exoskeleton is commercialized with the name "Armeo Power". [84-93]

"Maryland-Georgetown-Army exoskeleton" (MGA-exoskeleton) developed by Carignan and Lizka in 2005 allows 5 degrees of freedom including 3 degrees of freedom at the shoulder joint, 1 degree of freedom at elbow joint for flexion or extension, 1 degree of freedom for scapula motion. The first prototype is only for measuring the kinematics of the patient to adjust the passive linkage. The final prototype was developed in 2009, which is powered by harmonic drive transmission and brushless DC motors with optical absolute encoders for position. Force or torque sensors are used to measure forces and torques acting on the handle. The exoskeleton exerts forces at the hand that are sensed by force sensor at the handle and interacted with a virtual environment simulating daily living tasks for functional rehabilitation. Apart from the virtual reality mode, it also operates in physical therapy mode to allow the patient's arm to rotate about an axis through the shoulder with a programmable resistance profile. The spring length can be adjusted by therapist to select appropriate amount of assistive force for the patient. The movement of the arm will be measured by several sensors and displayed graphically on the computer screen and therefore patient can monitor the arm movement. [94, 95]

"Motion Assistive Robotic-Exoskeleton for Superior Extremity" (ETS-MARSE) developed by École de Technologie Supérieure (ETS) in Canada in 2014 allows 7 degrees of freedom including 3 degrees of freedom at the shoulder joint, 1 degree of freedom at elbow joint for flexion or extension, 1 degree of freedom at forearm for pronation or supination, and 2 degree of freedom at wrist joint for flexion or extension and radial or ulnar deviation, which aims at assisting daily upper limb movements and providing rehabilitation therapy for upper limb. The exoskeleton is made using aluminum, weighs 7.072 kg and is actuated by brushless DC motors with harmonic drives (HD) that have low or zero backlash properties and are backdrivable. A 6-axis force sensor is attached to the wrist handle for measuring the instantaneous force from the wearer to actuate the exoskeleton to provide assistance actively. [96]

There are some passive rehabilitation robotic devices such as Hand Motion Assist Robot [97], IntelliArm [98] and iHandRehab [99], focusing on hand and wrist rehabilitation only, while WaveFlex CPM [100] is focusing on fingers rehabilitation after stroke and HIT CPM [101] are focusing on the rehabilitation of hand injuries. Also, several novel rehabilitation devices for the hand are proposed by Iqbal et al. from 2009 to 2014, and the two most popular devices are the fingers and hand exoskeleton system HEXOSYS-I and HEXOSYS-II. [102-108] For active rehabilitation exoskeleton devices, there are several notable examples developed by research groups at Dartmouth Medical Centre USA [109], Politecnico di Milano Italy [110], Sabanci

University Turkey [111], Hong Kong Polytechnic University [112] and KAIST Korea [113], which are also focusing on the fingers and hand rehabilitation.

2.4.3. Orthotics for tremor suppression and analysis

Several systems and devices were developed by different research groups specifically for tremor management and suppression. The increase in damping and / or inertia in the upper limb were approved clinically to suppress the tremor by applying mechanical loading to the targeted limb in the literature, which suggests orthotic treatment to tremor suppression. There are basically two approaches to apply biomechanical loading either by exoskeleton robotic device or by non-wearable, object mounted end effector.

A table-mounted tremor suppression device “Neater Eater” was first developed by Michaelis Engineering to assist eating with 2 degrees of freedom damping, which turned into a commercially available product. [13] The “controlled Energy-Dissipation Orthosis” (CEDO) and the second generation of CEDO “Modulated Energy Dissipation Manipulator” (MEDM), developed by the Massachusetts Institute of Technology are the examples of the non-wearable, wheelchair mounted tremor suppression prototypes by applying resistive forces via magnetic particle brakes to the attachment on the wrist of the patient. The mechanism of CEDO allows the wrist 3 degrees of freedom in 2 dimensional space while that of MEDM allows the wrist 6 degrees of freedom in 3 dimensional space. [18-21] MIT Damped Joystick from the same research group is developed to enhance the control of the powered wheelchairs and other controllable devices by patients with tremor. However, the system is bulky and non-portable. [14-17]

“Hand-held gyroscopic device” invented by Hall is using the gyroscopic effect of a single rotating mass to reduce the tremor, which does not create damping effect to the tremor effectively since it only gives loading to the hand about the axis orthogonal to the rotating axis of the tremor. [114] Apart from the “Hand-held gyroscopic device”, another wearable tremor-suppression device ”Viscous Beam” developed in 1998 by the University of California Davis to suppress tremor by using the viscous damping only in 1 dimension i.e. extension and flexion of wrist and its damping frequency is not variable for different patients, which constrains the abduction–adduction and pronation–supination of the wrist. [22] In order to improve the performance, a similar concept of ”Viscous Beam” developed by Loureiro et al. using magneto-rheological fluids to control the attenuation actively and dynamically in response to the instantaneous frequency and amplitude of the tremor. [23]

Under the European project “dynamically responsive intervention for tremor suppression” (DRIFTS) (EU QoL QLK6-CT-2002-00536), the “wearable orthosis for tremor assessment and suppression” (WOTAS) exoskeleton weighs 0.85 kg and is developed in 2007 to measure and suppress the movement disorders like tremor by using electric motors at the wrist and elbow joints to actuate suppression and gyroscopes and kinetic sensors to measure the movement via both active and passive approaches. In order to identify the intended motion and tremor, real-time filtering algorithms and impedance control strategy are applied. Impedance control strategy lets patient be assisted only when it is needed. For the passive approach, a constant damping frequency applied to suppress tremor, however, is proved to be less effective than the active one. The viscosity or inertia of the damping is changed actively according to the biomechanical properties of each patient and therefore the efficiency of reduction in tremor reaches at 90%. The device is still large and heavy for patients to wear. [24-28]

An experimental smart glove developed by Universiti Teknologi Malaysia (UTM) in 2010 uses piezoelectric actuator to control the hand tremor. Since the piezoelectric actuator is utilized in the design of the glove, the size of it is small and it is light in weight. However, the voltage applied to the piezoelectric actuator is too high to have risk of electric shock to the wearer. [30] A conceptual design of orthotics was suggested using conducting polymer actuators to provide enough actuation force for tremor suppression within the range of tremor frequencies, [31] while another orthotics were developed using magneto-rheological dampers [32] or electromagnetic friction brake [33] to suppress the tremor actively with dynamical and variable damping force.

2.5. Future development

A soft cable-driven Exosuit developed by Asbeck et al. in 2013 does not consist of rigid frame structure but some webbing straps with geared motors to be the actuators via Bowden cable connected to the suit at the ankle joint. As the cable is not actuated, the suit can also provide some passive forces to the wearer because of the elastic properties of the fabric webbing. [115] Apart from using the geared motors, there is another research group from Harvard University using similar structure but pneumatic system to deliver actuation forces to the wearer via pneumatic artificial muscles (McKibben). [116] The same research group joint with Carnegie Mellon University developed a prototype called “Second Skin” using their own designed two-dimensional structured elastomer artificial pneumatic muscles in 2014, which can remove those useless empty volumes to acquire a zero-volume air chamber and therefore the structure can be made more compactable and light. [117]

Recently, there is a new type of wearable “soft” robots developed in 2014 by research team leaded by Rebecca Kramer, an assistant professor of mechanical engineering at Purdue University, using robotic fabric to be the structure, actuators and sensors of the robotic system. The robotic fabric is a cotton material including flexible polymer sensors and shape-memory alloy. As the shape-memory alloy is heated, it will return to its coiled shape and hence the fabric moves and can actuate the structure attached. However, the actuation response time for shape-memory alloy is long that this makes its application being limited to mechanism system accepting slow reaction. [118, 119] With soft sensors being integrated into these kinds of soft artificial muscles, their actuation such as strain, pressure, shear force and shape changing can be detected in real-time directly without changing much of the volume and weight.

In future, the prostheses and exoskeletons could be controlled by the thought of the wearer instead of detecting small forces, displacements or even the electromyographic (EMG) signal from the muscle that may not be detected for the quadriplegic wearer, which involves the development of brain-computer interface (BCI) technology. BCI have been applied to robotic prosthesis and several research groups are still investigating its application to exoskeletons now such as European union-funded "Mindwalker" project with non-invasive BCI technology and the dynamic recurrent neural network (DRNN) technique[62-63], and a full-body exoskeleton EMY (Enhanced Mobility) with invasive implant, the Wimagine, inserted on the surface of the motor cortex of the brain.[64-65] However, the brain signal data acquired by the sensors still need a long period of time to be interpreted so as to turn it into a practical device. Once all the above technical challenges are being solved, exoskeletons and even prostheses could then be really ready to replace wheelchairs and / or crutches.

2.6. Summary

The above review has shown most of the past and current research development of wearable robotic devices from military to non-military applications in order to assist human physical movement and actuation via the human-robot interface, which is summarized in the Table 1. Although there are some wearable robotic device researches being commercialized successfully in the market, exoskeletons for upper limb are still bulky and heavy to the wearer, especially for those patient with neural disorder disease like Parkinson's disease or essential tremor.

Basing on the work of "wearable orthosis for tremor assessment and suppression" (WOTAS) [24-28], this project develops and investigates the use of wireless motion capture system "BSN" and motors to acquire the motion of the tremor and real time control of the motor to suppress the tremor motion as an alternative to provide a light, slim and functional tremor suppression wearable device.

Wearable Robots	Type	Applications
ReWalk	Lower limb	Assist individuals with thoractic-level complete SCI to walk
MS-02 PowerLoader	Full body	For nuclear industry use, e.g. clean up work in the Fukushima Daiichi nuclear power plant
PLL-04 PowerLoader Lite (Ninja)	Lower limb	For nuclear industry use, e.g. clean up work in the Fukushima Daiichi nuclear power plant
Hybrid Assistive Limb (HAL)	Lower limb, full body	Trains doctors and physical therapists, assists the disabled to walk, works to carry heavy loads
Berkeley Lower Extremity Exoskeleton (BLEEX)	Lower limb	Military, health and medical use
Wearable orthosis for tremor assessment and suppression (WOTAS)	Upper limb	Tremor suppression
Smart glove developed by Universiti Teknologi Malaysia (UTM) using piezoelectric actuator	Upper limb	Tremor suppression
Orthotics using conducting polymer actuators	Upper limb	Tremor suppression
Orthotics using magneto-rheological dampers	Upper limb	Tremor suppression
Orthotics using electromagnetic friction brake	Upper limb	Tremor suppression
MIT Exoskeleton	Lower limb	Military use
Active Knee Rehabilitation Orthotic Device (AKROD)	Lower limb	Rehabilitation after stroke

Magneto-rheological fluid (MR) brake AFO	Lower limb	Ankle Rehabilitation
MIT active ankle-foot orthosis (MIT-AFOs)	Lower limb	Ankle Rehabilitation
HONDA Walking Assist Device, HONDA Bodyweight Support Assist	Lower limb	Assist walking for those with muscle weakness and reduce load on leg muscles
Human Universal Load Carrier (HULC)	Lower limb	Military use
XOS 2	Full body	Military use
Ekso (formly eLEGS)	Lower limb	Assist patient with difficulties in sitting, walking and standing
REX Rehab, REX Personal	Lower limb	Assist patient with high level of mobility impairment, e.g. paraplegics, quadriplegics
Hercule V3	Lower limb	For manufacturing industries and construction sites use
AlterG Bionic Leg	Lower limb	Designed for hemi-paresis, rehabilitation after stroke
Soft cable-driven Exosuit developed by Asbeck et al.	Lower limb, soft	Assist walking for healthy individual and those with muscle weakness
Second Skin	Lower limb, soft	For rehabilitation of injured nervous systems
Mindwalker	Lower limb	Designed for paraplegics to restore locomotion capability
EMY (Enhanced Mobility)	Full body	Designed for quadriplegics to restore mobility
WaveFlex CPM	Upper limb	Hand rehabilitation
HIT CPM	Upper limb	Hand rehabilitation
HEXOSYS-I and HEXOSYS-II	Upper limb	Hand rehabilitation
Dartmouth Medical Centre exoskeleton	Upper limb	Hand rehabilitation
Politecnico di Milano exoskeleton system	Upper limb	Hand rehabilitation
Sabanci University exoskeleton	Upper limb	Hand rehabilitation
Hong Kong Polytechnic Univeristy exoskeleton	Upper limb	Hand rehabilitation
KAIST exoskeleton	Upper limb	Hand rehabilitation

Table 2.1 Wearable robots and their applications.

3. Voluntary and involuntary motions study

This chapter will describe the methodology of measuring the motion with a wireless motion capture system and the analysis of the data from sensors. Feature extraction and classification of the voluntary and involuntary motions will be explained how different human behavior with tremor can be determined basing on the raw data from the sensors and corresponding sensor algorithm.

3.1. Sensors

In order to extract several hand-wrist-forearm motion parameters for biomechanical analysis, a wireless Inertial Measurement Unit (IMU) sensor system “Body Sensor Network Operating System (BSNOS)” was used to capture the motion from the hand and forearm accurately in low energy consumption.

3.1.1. System specifications

BSNOS is an open source development platform specifically for BSN applications. [120] The system includes BSN node and base station. BSN node, see Figure 3.1, is in the size of 29 x 19 x 18 mm and consists of eight major components, i.e. microcontroller, radio transceiver, flash memory, LEDs, BSN board connectors, mounting for antenna, battery and sensor, while base station, see Figure 3.2, is the transceiver interface communicating between the computer connected via USB cable and the wireless BSN node sending incrementing number every time in 18 byte message at the frequency 20 Hz. [121] Several applications using BSNOS were published that it can let researchers not only control the LED, but also gather the signals from accelerometers, gyroscopes and magnetometers, and send signals back to the base station and hence the computer can analyse the data and further applications. [122, 123]

Figure 3.1 Wireless BSN node of the Body Sensor Network Operating System (BSNOS).

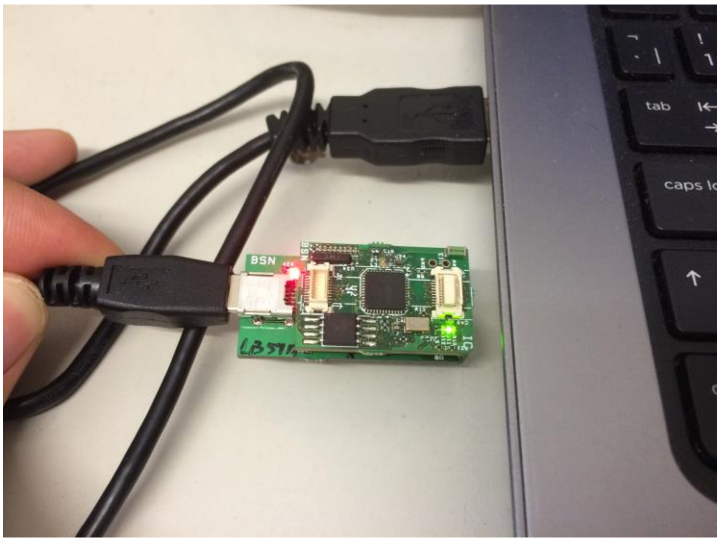


Figure 3.2 BSN basement of the Body Sensor Network Operating System (BSNOS) connecting to the computer via USB cable.

3.1.2. Feasibility validation

Tremor, involuntary motion, is different from those voluntary motions. The frequency range of tremor motion is from 2 to 12 Hz, which is higher than the intended motion that is within 1 to 2 Hz. Therefore, the system and the sensors should be sensitive and accurate enough to measure and detect the motion of the tremor for that frequency range.

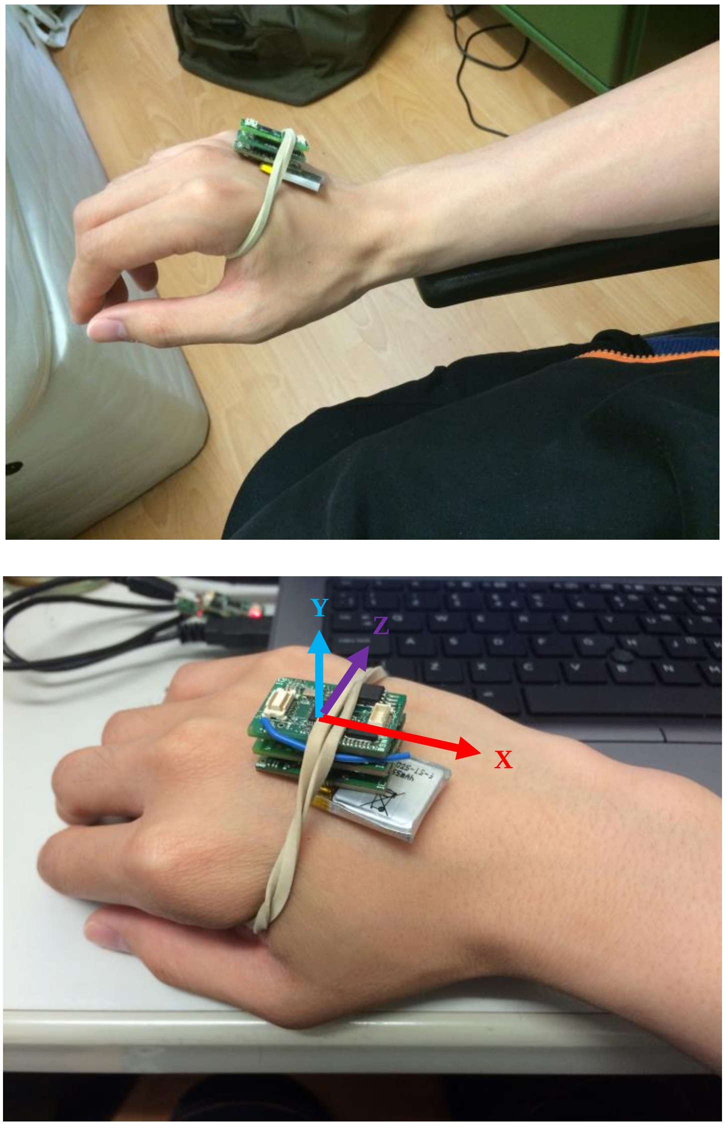


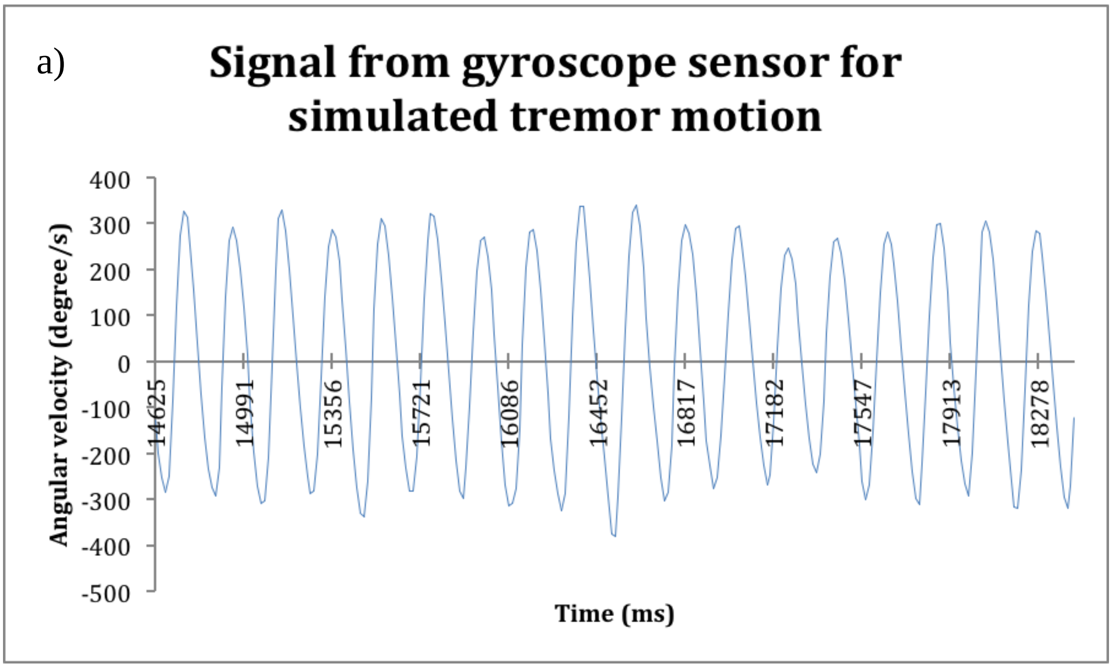
Figure 3.3 BSN node with sensor is placed over the third metacarpal of the hand.

Since our project is mainly focus on the research development of the tremor motion at the wrist joint and suppressing the tremor of hand with respect to the body, the BSN node with a tri-axial accelerometer and a tri-axial gyroscope was placed over the third metacarpal of the hand, see Figure 3.3. The standard sensor coordinate system of the BSN node is defined relative to the hand. The X-axis is horizontal and points to the right, the Y-axis is vertical, perpendicular to the hand, and points upwards, and the Z-axis points out of the plane perpendicular to the hand. Therefore, the coordinate system of the gyroscope and accelerometer is the same as the standard sensor coordinate system, where G_x, G_y, G_z are the rate of rotation around the X-axis, Y-axis and Z-axis respectively, and A_x, A_y, A_z are the acceleration along the X-axis, Y-axis and Z-axis respectively (including gravity). The following movements were measured as they are the most important articulations in the kinematics of upper limb for tremor validation [28]:

- Wrist flexion-extension
- Forearm pronation-supination

The signal presented in Figure 3.4a and 3.4b was measured by the gyroscope and the accelerometer from a normal person without neural disorder disease simulating a Parkinsonian resting tremor movement for the flex-extension of the wrist around the Z-axis and along Y-axis respectively. In order to attenuate the high frequency noise signal, the original signal collected from the sensors will be filtered by digital 2nd order low-pass Butterworth filter with cut off frequency at 20 Hz in 1000 Hz sampling rate. The filtered signal is clearly showing the sinusoidal pattern representing the motion of the hand vibrating up and down for the flex-extension of the wrist and the time intervals of the patterns reflect the frequencies of the tremor, i.e. about 5 Hz from Figure 3.4, and therefore using these two types of sensors in determining and detecting the tremor motion is feasible.

Since gyroscope provides the absolute angular velocity along each axis without any external reference, the frequency and amplitude of the signal acquired from it will not be influenced by other factor, however, the accelerometer will be affected by gravity. Therefore, the signals from accelerometer and gyroscope can compensate the disadvantages of each other to provide extra information for behavior classification analysis.



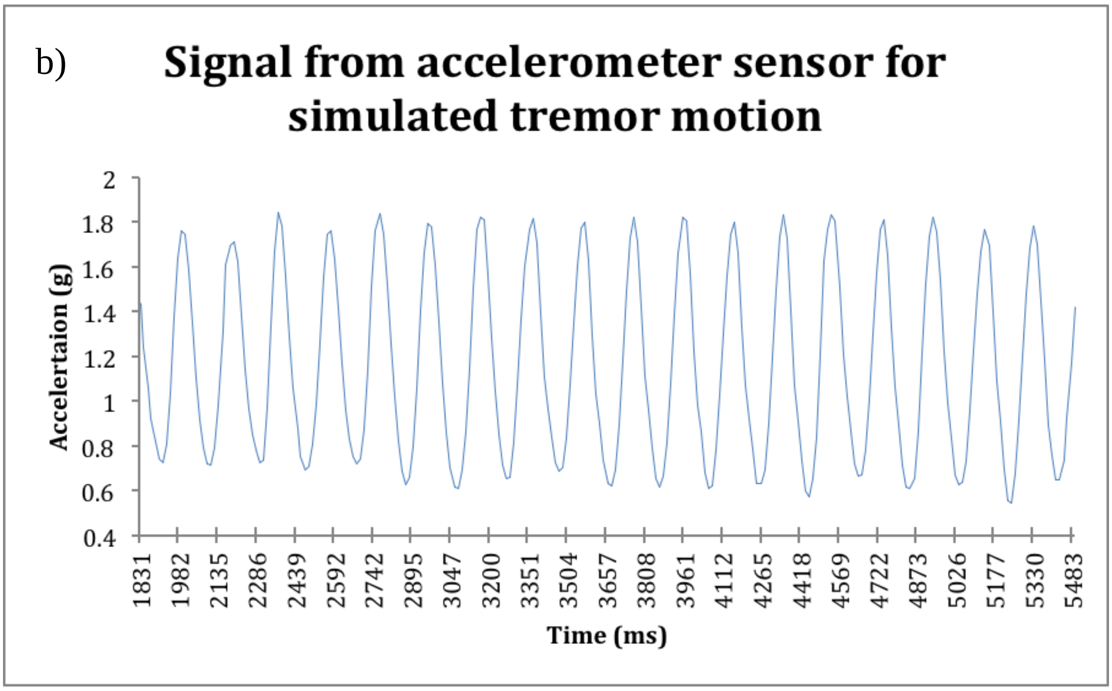


Figure 3.4 The signal shown was measured by a) the gyroscope and b) the accelerometer from a normal person without neural disorder disease simulating a Parkinsonian resting tremor movement for the flex-extension of the wrist around the Z-axis and along Y-axis respectively.

3.2. Tasks

In order to study the real daily life behavior, an experimental protocol of seven different tasks was set to get enough data for analysis. Six healthy volunteers (three male and three female volunteers of the age from 20 to 28) were recruited and asked to do all the tasks with and without the high frequency vibration motion (about 3 Hz) simulating tremor movement for 30 seconds each task in their own style, and the sensor signals from both the gyroscopes and accelerometers were captured. Since the most of the tremor motions involve the flexion-extension of wrist and the pronation-supination of forearm, according to the clinical study [124], the vibration motion at about 3 Hz of the flexion-extension of wrist is selected to simulate the tremor movement by the volunteer. The six tasks are:

1. Sitting: the volunteer was asked to sit down and put his/her hand on the thighs with the arms in the rest position.
2. Walking: the volunteer was asked to walk for several steps with two arms swinging normally.
3. Running: the volunteer was asked to run.
4. Pointing an object: the volunteer was asked to point at an object at the breast height in front of him/her from a rest position of the arm. The distance between the shoulder and the finger was about 60% of the length of the whole arm.
5. Moving a bottle of water: the volunteer was asked to grab a bottle of water and move it to the left in a distance away from the original position and back to the original position. The positions of starting point and the target point were marked by a cross of black tape on the table. The distance between two points is 20 cm.

6. Holding a bottle of water while walking: the volunteer was asked to walk and hold a bottle of water at the same time. The bottle of water was in upright position as the elbow remained flexed at 90 degrees.

Apart from Task 2, 3 and 6, the volunteer was sitting on a chair for all other tasks. Figure 3.5 illustrating the volunteer performing those six different tasks mentioned above.

For a higher efficiency in data collection and labeling, all the tasks were recorded for 30 seconds and saved separately in different files. About 2050 data were generated for each task in 30 seconds with the resolution of 0.014625s and frequency at around 68 Hz, and therefore there were 28,700 data for each volunteer.

Figure 3.5 The healthy volunteer performing six different tasks: a) Sitting, b) Walking, c) Running, d) Pointing an object, e) Moving a bottle of water, f) Holding a bottle of water while walking.

3.3. Results

From the figure 3.6 and 3.7, it shows the signal magnitude vector (SMV) of the raw data from accelerometer and gyroscope correspondingly from one of the volunteers, which is calculated by the equation:

$$A_{smv} = \sqrt{A_x^2 + A_y^2 + A_z^2}$$

$$G_{smv} = \sqrt{G_x{}^2 + G_y{}^2 + G_z{}^2}$$

where A_{smv} is the signal magnitude vector (SMV) of the acceleration, A_x, A_y and A_z are the acceleration along the X-axis, Y-axis and Z-axis correspondingly, while G_{smv} is the signal magnitude vector (SMV) of the angular velocity, G_x, G_y and G_z are the angular velocity around the X-axis, Y-axis and Z-axis correspondingly. The reason of using the two SMVs rather than three different vectors (x,y,z) is that they are insensitive to orientation and position, and therefore various orientations and positions of the sensor will not need to be discriminated.

The figures illustrate the capability of using gyroscope and accelerometer to capture the information of different activities as it shows that different patterns and waveforms of the signal can be discriminated and identified for each of the six activities with and without the simulated tremor motion. Although the signals from both gyroscope and accelerometer with tremor motion are dominated by sinusoidal pattern caused by the tremor motion, the six activities can still be barely distinguished by the amplitude and frequency of the patterns.

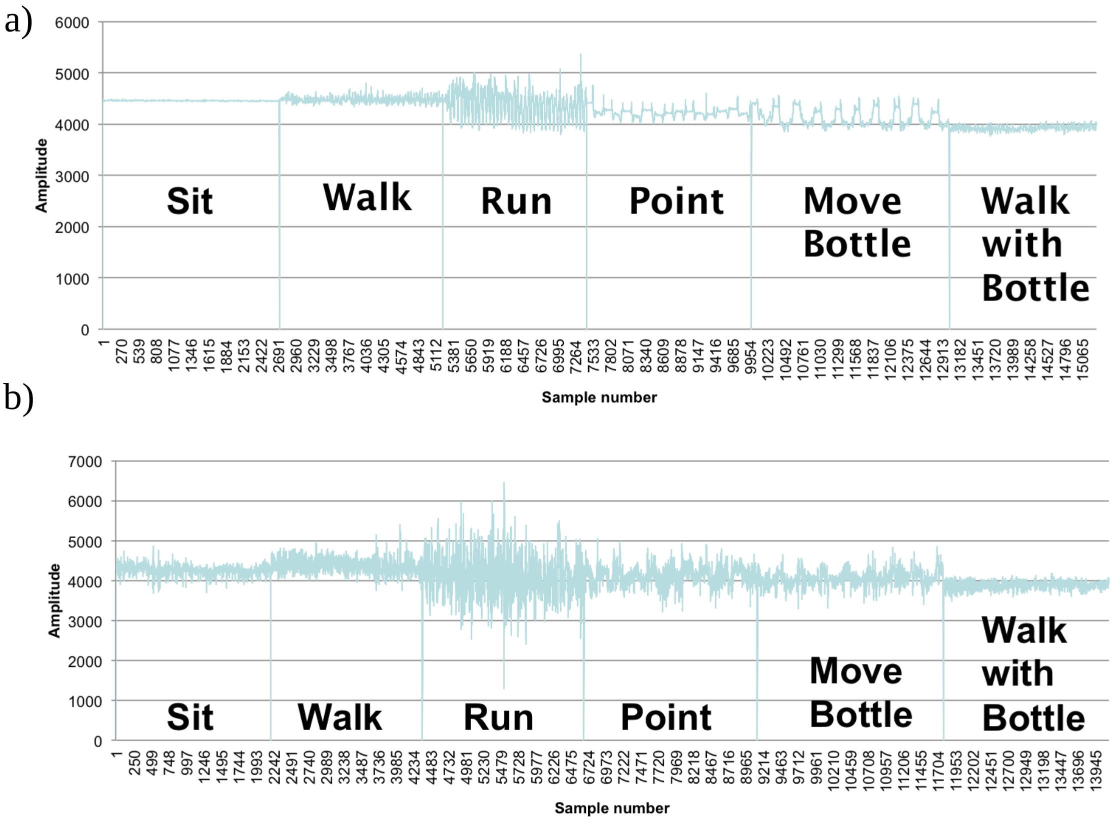


Figure 3.6 The signal magnitude vector (SMV) of the raw data from accelerometer for the six activities a) without and b) with simulated tremor motion.

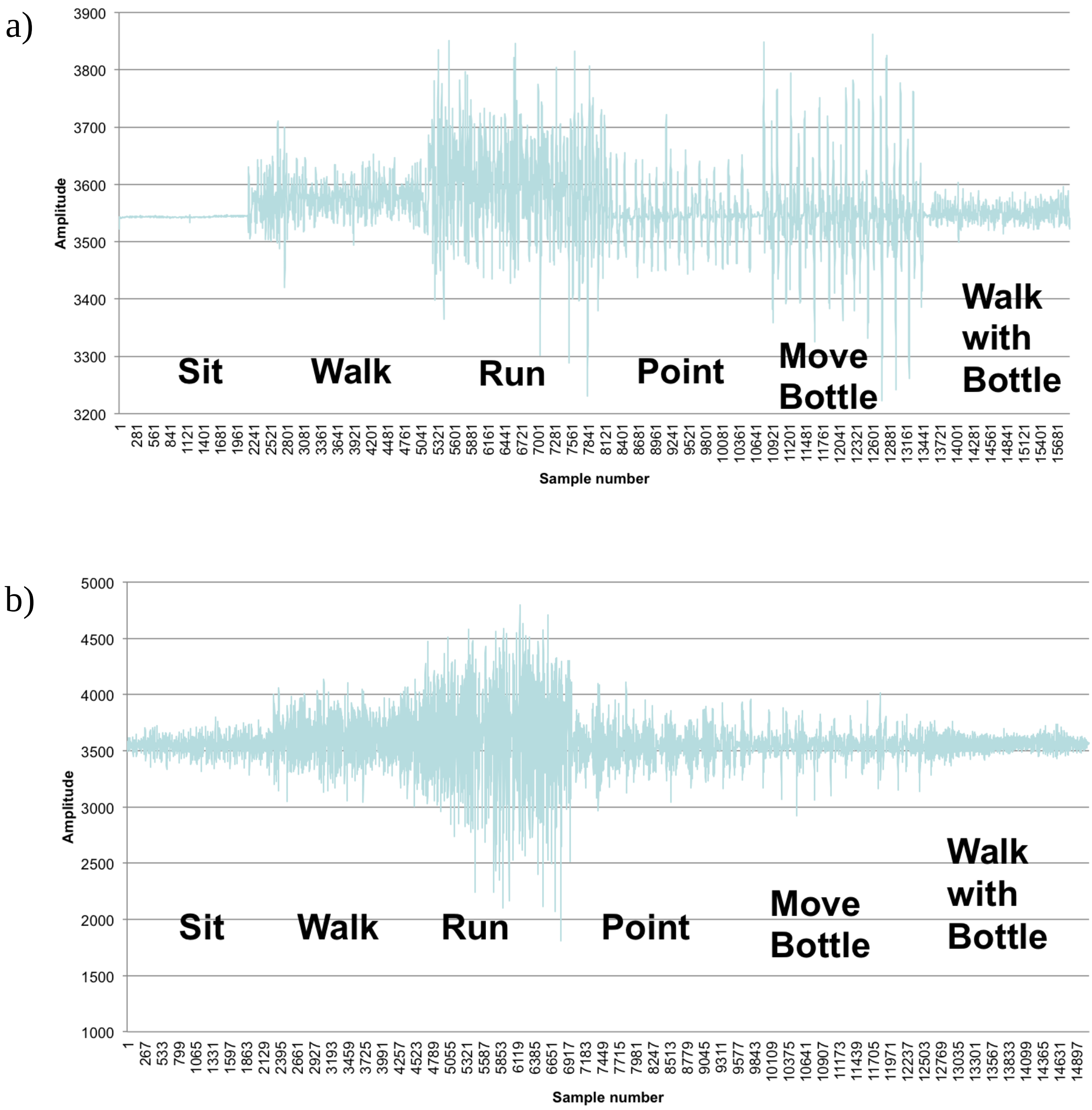


Figure 3.7 The signal magnitude vector (SMV) of the raw data from gyroscope for the six activities a) without and b) with simulated tremor motion.

3.4. Data analysis

After all the raw data signals were collected, they were filtered using analog filter with the same setting in section 3.1.2 for pre-processing. Then the filtered signals were decomposed into tremor and voluntary motion with two different methodologies:

1. Manual decomposition

   The filtered signals were decomposed by a digital pass-band Butterworth second order filter into tremor and voluntary motion with ad hoc setting manually. For voluntary motion, the cutoff frequencies of the filter was set to 0 to two Hz to separate the signal of voluntary motion from the input signal. For the detection of the tremor motion T_{man}, the cutoff frequencies of the filter were set to 2 to twenty Hz instead. According to some researches published previously, the frequencies of voluntary motion were usually lower than 2 Hz, while that of tremor was shown to be at higher range from 2 to twelve Hz. [125, 126] Figure 3.8 shows the example of the signal decomposed manually into the tremor and voluntary motion.

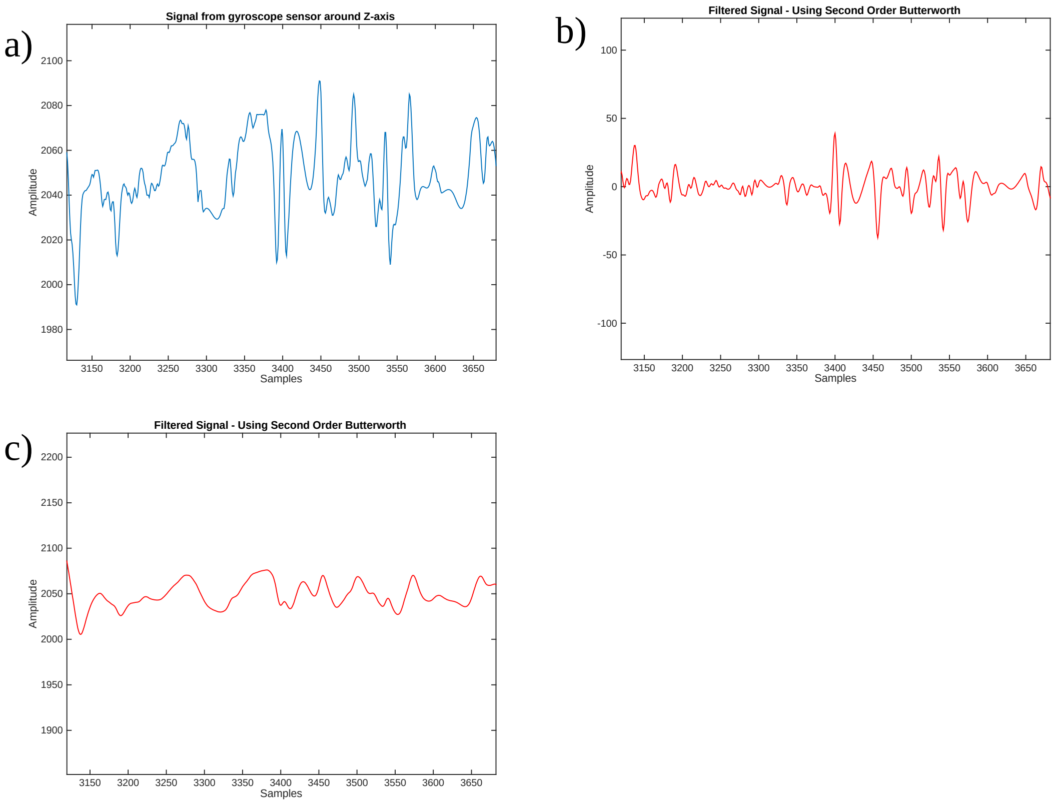


Figure 3.8 a) The raw signal from gyroscope around Y-axis was decomposed manually into b) the tremor and c) the voluntary motion by a digital pass-band Butterworth second order filter.

2. Automatic decomposition

   The filtered signals were decomposed by the Empirical Mode Decomposition (EMD) automatically, where the filter settings were automatically provided by the adaptive method. [127] The EMD will decompose the time series signal into intrinsic mode functions (IMF), which can be used to identify the tremor and voluntary motions. Figure 3.9 shows the example of the signal decomposed by EMD in Matlab program based on the book [128], into the tremor T_{auto} and voluntary motion automatically. Eight intrinsic mode functions (IMF_1, IMF_2, IMF_3, IMF_4, IMF_5, IMF_6, IMF_7, IMF_8) were obtained, where IMF_1 is the finest time-scale component and IMF_8 is the largest time-scale component of the signal.

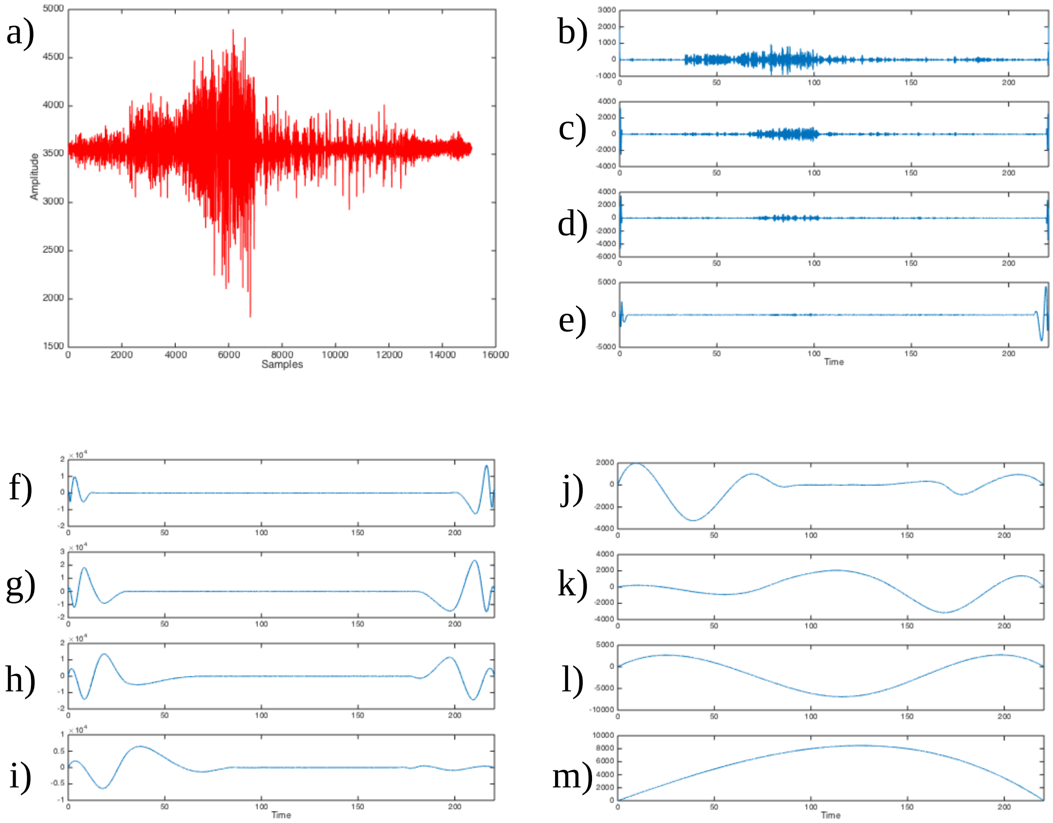
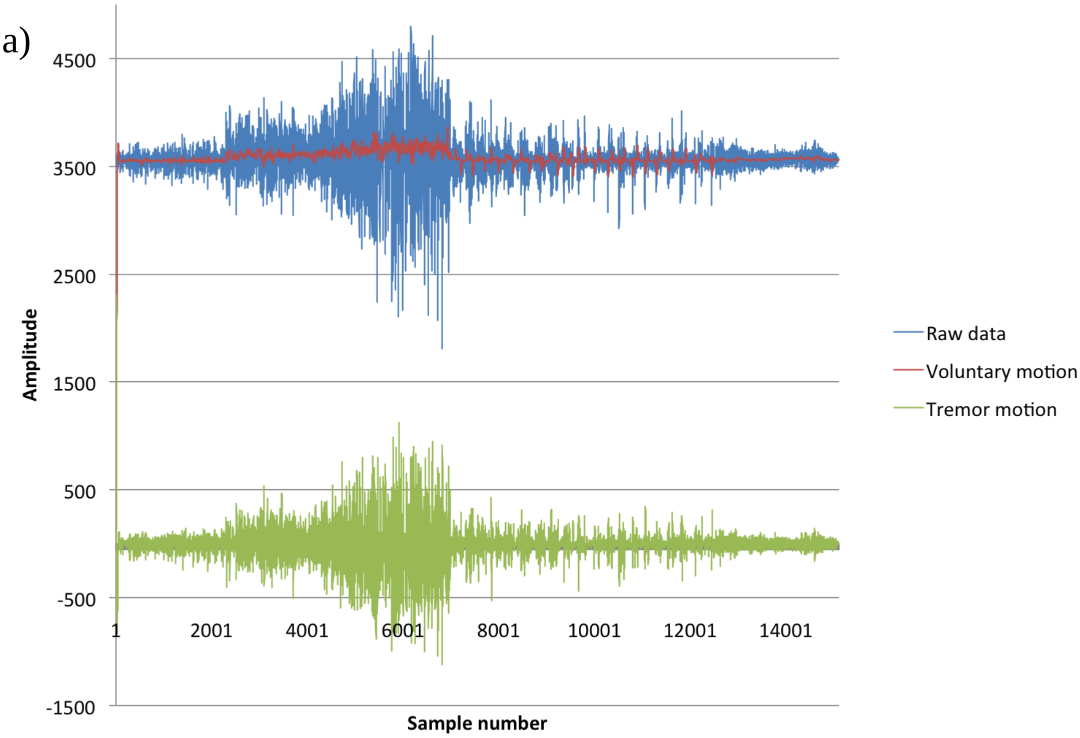


Figure 3.9 a) The raw SMV signal from gyroscope was decomposed by the Empirical Mode Decomposition (EMD) automatically into twelve intrinsic mode functions: b) IMF_1, c) IMF_2, d) IMF_3, e) IMF_4, f) IMF_5, g) IMF_6, h) IMF_7, i) IMF_8, j) IMF_9, k) IMF_{10}, l) IMF_{11}, m) IMF_{12}.

Therefore, the tremor motion estimated manually was compared with that extracted by EMD automatically. By comparing the tremor signal obtained manually and the above twelve IMFs, it was found that the sum of IMF_1, IMF_2 and IMF_3 is the best estimation and representation of tremor signal while the sum of the rest IMFs apart from IMF_1, IMF_2 and IMF_3 can retain the voluntary motion, see figure 3.10.

a)



b)

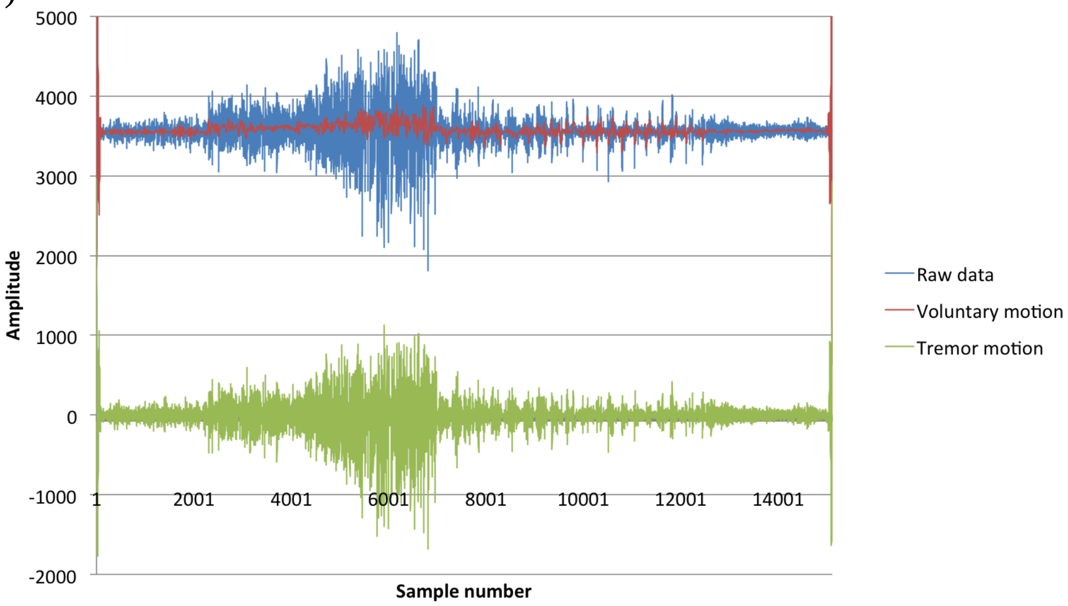


Figure 3.10 the comparison of the raw data, voluntary motion and tremor motion decomposed by a) manually and b) automatically.

4. Tremor suppression system

After the study of the tremor motion, a wearable hardware device was designed, developed and tested by several healthy volunteers in order to implement the idea for the proof of concept. The prototyping development process was divided into three parts shown in the figure 4.1. First, a rigid was designed and developed to simulate the tremor motion and evaluate the tremor suppressing system. Then, an initial design of wearable suppression system was evaluated to determine the potential structural design of the prototype before a 3D printed working prototype was developed.

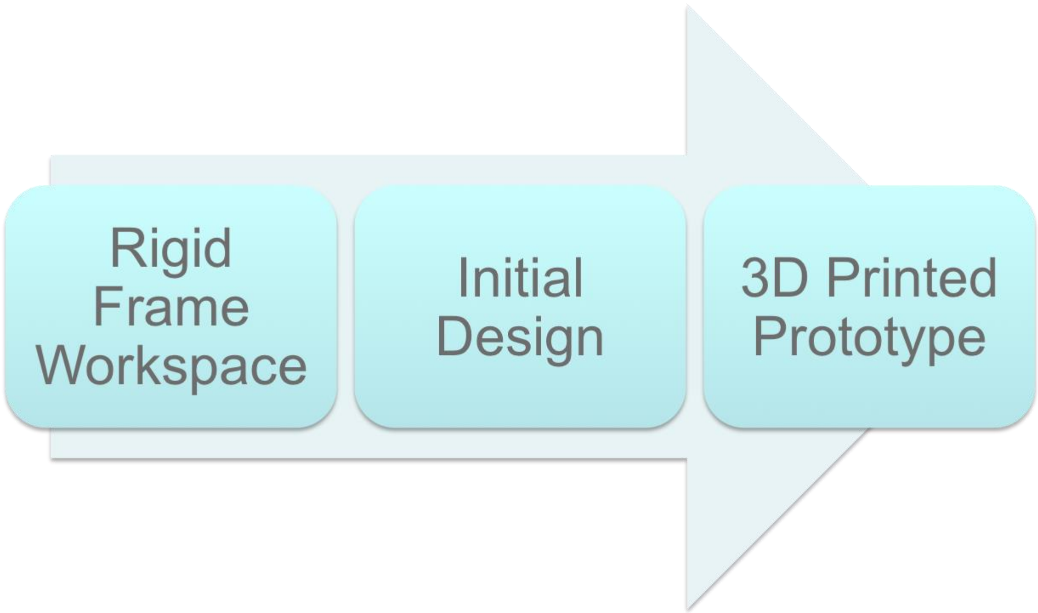


Figure 4.1 The prototyping development process was divided into three parts.

4.1. System specification

The objective of the development of the working prototype is to test and prove the feasibility of the concept of the tremor detection and control system using simple and market existing motors with the low computing cost algorithm that lead to a portable, light wearable exoskeleton robotic device. The USB motor control interface, USB2Dynamixel, microcontroller CM-700 and DYNAMIXEL geared motors from the company called ROBOTIS were selected to build the prototype, see Figure 4.2.

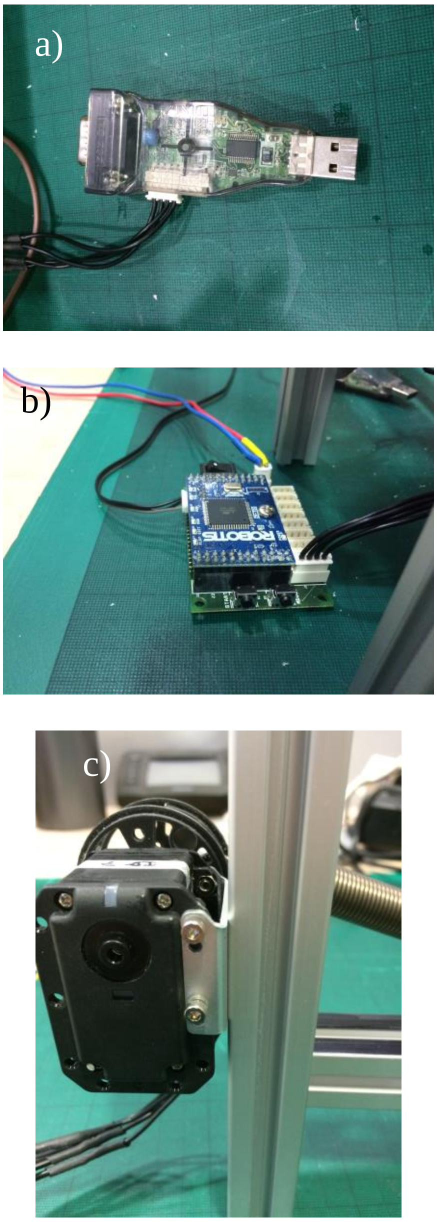


Figure 4.2 a) The USB motor control interface, USB2Dynamixel, b) microcontroller, CM-700, and c) DYNAMIXEL geared motors from the company called ROBOTIS.

Through the USB2Dynamixel interface, the control strategies can be programmed with different kinds of programming language and platform including MATLAB®, python, C/C++, Visual Basic, Java, LabVIEW, Microsoft Visual Studio, etc, with TTL/RS485/RS232 communication supported to control the DYNAMIXEL geared motors directly from the computer to the corresponding motors. Programs can also be downloaded to an external microcontroller to execute the program independently without connecting to the computer. CM-700 model that uses CPU, TTL/RS-485 communication circuit and ATMega 2561, supports GP I/O & ADC for analog sensor and zigbee or Bluetooth connection was also being used to control the DYNAMIXEL geared motors. DYNAMIXEL actuator series are those geared motors with many advantages such as simple connection structure via network, all-around assembling structure, motor status display function, compliance and torque setting, PID gain control, high voltage drive and low-electric current consumption.

4.2. Control strategy

The control strategy developed was aimed at evaluating the tremor suppression function of the device, which needs to provide feedback interaction to the hand and arm. According to the table 1.1, some researches were done showing the pathological tremoroue frequency having the range from 3 Hz to 12 Hz, while the frequency for daily life activities will be lower than 2 Hz. Therefore, the control system should be designed to be sensitive to these frequency cutoff ranges in order to execute the suppression function while the tremorous frequency is detected.

The control strategy we used in this study is a threshold method. The rate of change of position can be determined from the signals of position sensors inside the geared motors, and then the frequency of the motion is extracted to be interpreted for the activating the suppression function when the frequency detected surpasses the threshold value at 3 Hz. Execution signal is sent to the geared motors via the actuation controller to apply damping force to oppose or suppress the tremor motion. The idea of this control strategy is based on the assumption that tremor motion will have a higher frequency of changing the position crossing a baseline that is a dynamic reference position along the voluntary motion. The geared motors will keep on giving feedback position signal to the position sensor to update the frequency input to the detection system for the next execution of the suppression function.

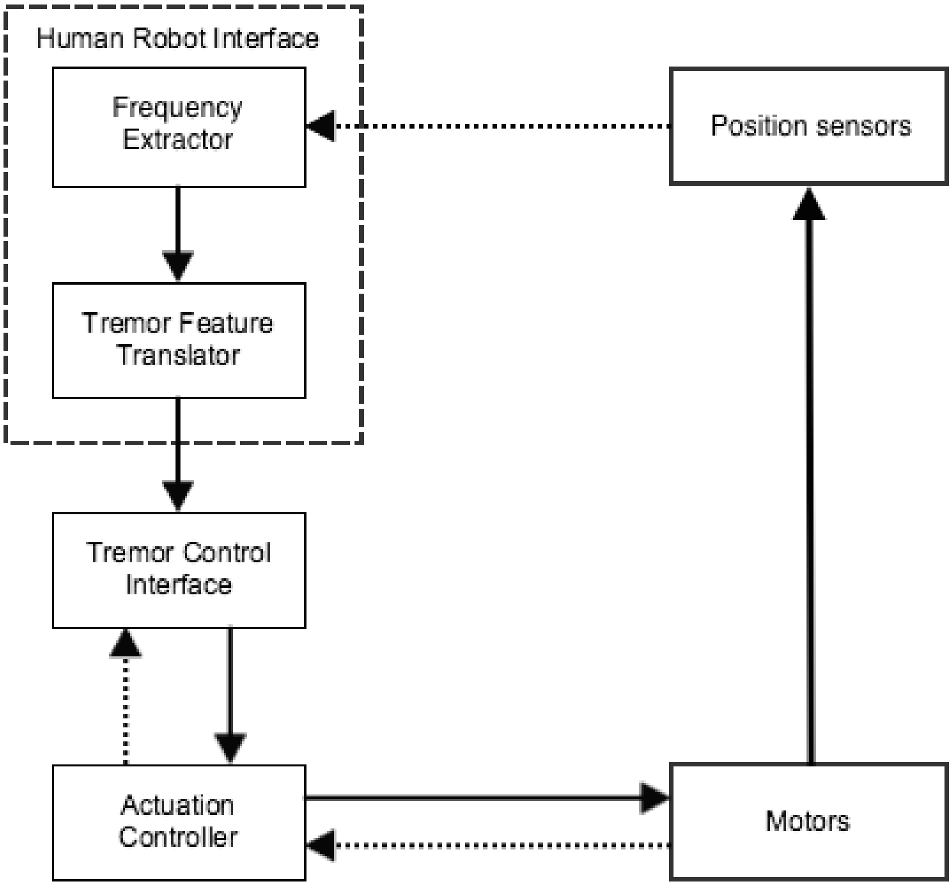


Figure 4.3 Control architecture strategies for the suppression function of the device.

4.3. Tremor motion and suppression simulation in rigid frame

A rigid frame working space, see Figure 4.4, was designed and developed in order to simulate the tremor motion and evaluate the tremor suppressing hardware structural design and its control algorithm before the wearable suppression system was started being designed.

The rigid frame working space was built from aluminum rods that can be put on any flat surface like desktop to provide a stable space for the tremor motion simulation.

The structure of human hand was simulated by a metallic linear cylinder, which was connected to a one-dimensional joint that mimicking the wrist joint. The tremor motion of wrist flex-extension and the forearm pron-supination were simulated by two DYNAMIXEL geared motors that were controlled by the CM-700 microcontroller and therefore the frequencies and torques of the simulated tremor motion can be tuned to the values similar to that from the Parkinson’s disease or Essential tremor patients. In order to choose the right actuator that has enough power for the tremor suppression device, the amplitude of the torque of the tremor motion is important apart from the tremorous frequencies. According to the research published by Rocon et al. 2007 [129], the mean value of torque needed to suppress the tremor motions in forearm pron-supination joints is around 3 N.m while that in wrist flex-extension is around 1 N.m. Therefore, four suitable DYNAMIXEL geared motors were chosen to simulate and suppress the tremorous torque and frequencies. Two of the motors were arranged and operate in the two different directions to simulate the tremor motions in forearm pron-supination joints and wrist flex-extension, while other two motors were arranged in opposite direction to demonstrate the suppression control system.

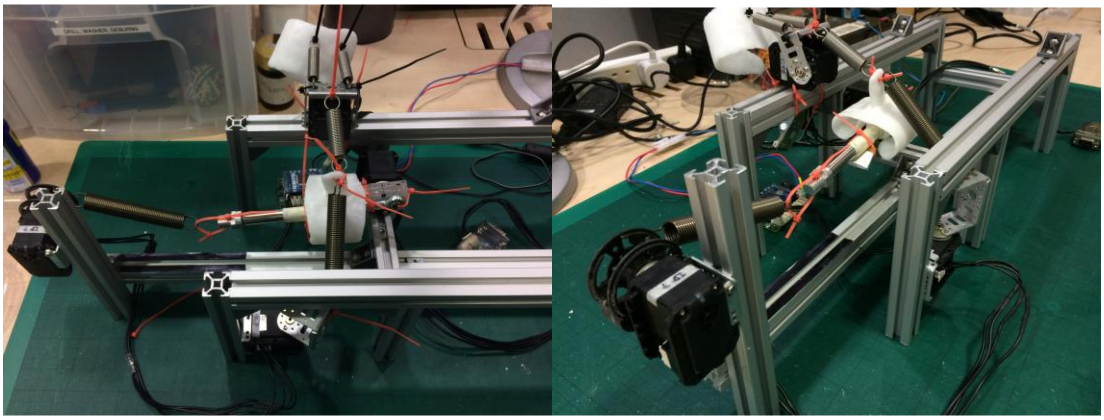


Figure 4.4 The aluminum rigid frame working space with a metallic linear cylinder simulating the structure of human hand and the wrist joint. Four DYNAMIXEL geared motors were used to simulate and suppress the tremorous torque and frequencies.

The two motors were programmed to move from one goal position to another goal position back and forth in an infinitely loop continuously to simulate the tremor vibrational motion in a frequency measured and determined by the BSN wireless node system. The other two motors were installed to the rigid frame working space for mimicking the situation that the user is wearing the tremor suppression device without being activated, and the tremor vibrational motion was also simulated again by the same torque and rotational speed of the motors as the previous experiment. Then, the experiments were done again by activating the tremor control system, i.e. activating the tremor suppression after the tremor motion being detected.

4.4. Wearable device: design and mechatronics

In order to evaluate the real practice of the control system and strategies, a wearable robotic exoskeleton device was designed and developed. Since wearable robotic exoskeleton device provides feedback to the wearer while the wearer is controlling it with consideration of biomechanical interaction between human body and the robotic device so as to determine the forces and positions that needed to apply onto the body.

Therefore, a physical interface between the wearer and the robotic device is needed and so important that the design and architecture should consider the four criteria: safety, robustness, ergonomics and reliability.

4.4.1. Biomechanics of human hand and forearm

- Comfort capability

There will be pressure applied onto the hand and forearm via the human-robot interface during the operation of the device. The contact part between them should be comfortable to the wearer in order to transmit the load to the bone via the soft tissues, and the actuators on the device may apply resistant force on the hand and forearm by the damping effect. Therefore, the distribution of pressure on the body is an important parameter to be considered when designing the structure of the exoskeleton structure. There are two ways of strategies for the pressure distribution: concentrate the load to a small region for tolerating high pressure or distribute the load over a large region for reducing the pressure, and the latter one is adopted commonly to be the appropriate way to distribute the pressure. However, according to the research from Goonetilleke, there is a threshold that it is better to concentrate forces than to distribute that. [130] Also, another research from Krooskop et al. shows that restless can be caused by mattresses with uniform pressure distribution. [131] The reason can be explained by the Spatial Summation Theory that the excitation of skin receptors is increased as the contact area increases and eventually it becomes a worse comfort perception.

A study of biomechanics of upper limb was done for determining the limits of comfort related to the pressure applied on the corresponding area. [132] It found that there will be different in the perception of the pressure and the maximum pressure tolerance in different areas of the upper limb, see figure 4.5.

Figure 4.5 Different areas of the hand and forearm with different sensitivity to pressure: low tolerance at 450 kPa in average (yellow area), middle tolerance (orange area), and high tolerance at 950 kPa in average (red area).

- Stiffness of soft tissues at the upper-limb

As the tremor motion is dynamic, the stiffness of soft tissues is part of the key consideration for designing the device in order to have a high efficient transmission of the actuation force to the bones. The transmission between the bones and the device depends on the stiffness of the soft tissue between them. The soft tissues are including muscles, tendons, fat, and skin of the hand and forearm. According to the study done by Maurel et al., soft tissues have high non-linear biomechanical properties, which varies from one person to another person and change dynamically as the muscle are in contraction. Also, the stiffness of the tissue will increase with the stress. []

- Biomechanical movement of wrist and forearm

Figure 4.6 shows the flexion-extension movement of wrist and the pronation supination movement of forearm. Since the pronation-supination movement of forearm is a rotational movement of the forearm and the wrist along the longitudinal axis of two joints: upper radioulnar joint and the lower radioulnar joint. The rotational movement involves two bones in the forearm: ulna and radius. As the muscle in forearm contracts and extends, the ulna will stay while the radius will move and rotate towards the elbow and distally along the axis of the ulna bone. This biomechanical structure makes the mechanical design for controlling the pronation-supination movement more complex.

a)

b)

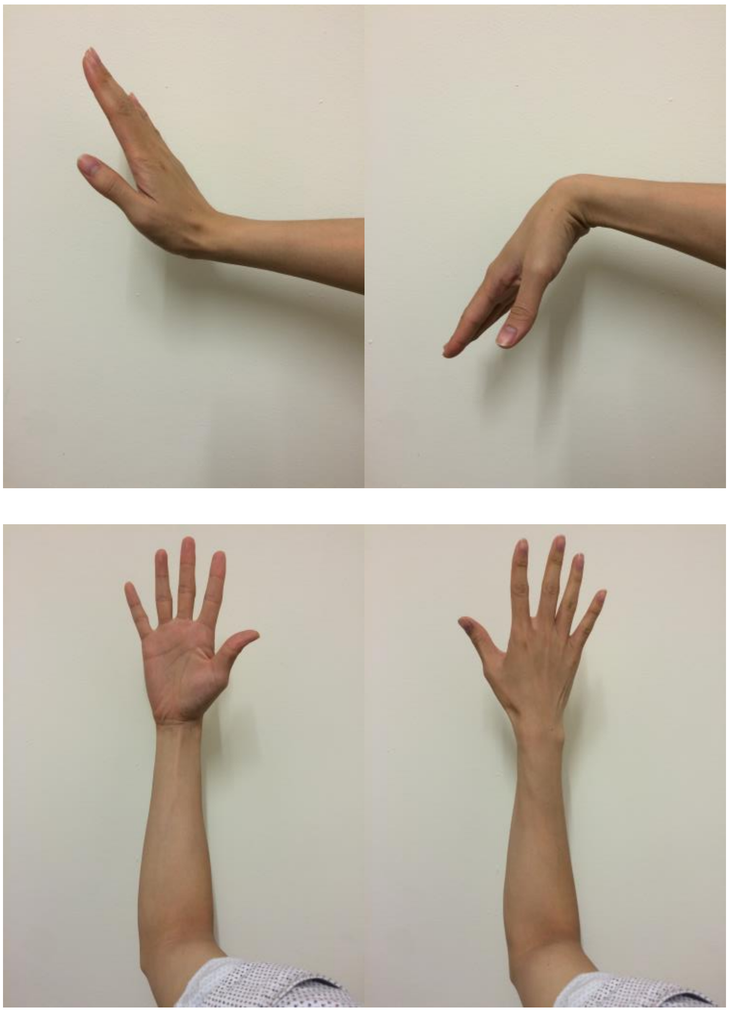


Figure 4.6 a) Flexion-extension movement of wrist and b) pronation-supination movement of forearm

4.4.2. Ergonomics structural design

Several points were considered when designing the structure of the device in order to fit for the shape and biomechanics of human body:

- Forces on the arm tissues must stay in acceptable limits
- Minimal interference by the forces applied on the wrist and forearm movement
- The interaction of the wearable device and the arm, i.e. the load transmission onto the arm with the optimum comfort feeling.
- Avoid any interaction with the bony prominences, joints, surface tendons and nerves, blood vessels.
- Since the mechanical structure of the wearable device must be ergonomically aligned with the upper limb and the material used for the structure should be strong and rigid enough to support and transmit the force from the actuators to the limb, the material PLA and ABS were used for making the structure of the device as they are the filament material for 3D rapid printing prototyping machine, i.e. Makerbot® and Ultimaker®, with that the size and structure can be customized according to different wearers at a lower cost.
- After the consideration of the pressure-comfort sensitivity distribution of the arm, the fix or contact points between the wearable device and the arm of wearer were chosen to be at the palm-dorsal of the hand, the edge of the forearm near the wrist, and the brachioradialis and flexor carpi radialis of forearm.

4.4.3. Actuators and sensors

Since the wearable device aims to detect and suppress the tremor motions in real time strategies, sensors and actuators are needed for the device. Sensors for kinetic (interaction force between the limb and device) and kinematic (angular velocity) are required for the input information to the control strategies in order to trigger the actuators. As mentioned in section 4.1, the DYNAMIXEL geared motors controlled with the USB motor control interface and USB2Dynamixel produced by the company called ROBOTIS were selected to build the prototype. According to the specification of the motor, several feedback parameters can be read from the motor in real time, i.e. current position, current speed, current voltage, current temperature, and status of moving. By programming to read those feedback values from the motor, the current position, angular velocity and frequency of the motion of hand and forearm can be determined since the actuators in the wearable device are being moved and rotated along with the hand and forearm of the wearer. For example, as the hand does not move, the current position, current speed and status of moving feedback from the motor will be a constant value byte, zero byte (zero speed) and zero byte (not moving) correspondingly.

Figure 4.5 shows the final design and configuration of the wearable robotic device for tremor suppression with DYNAMIXEL geared motors. Since, apart from actuators and sensors, most of the components were 3D printed by rapid prototyping machine with PLA and ABS plastic materials, the total weight of the final system is about 350g. An experiment testing protocol was set and performed to evaluate its function and workspace for a healthy volunteer.

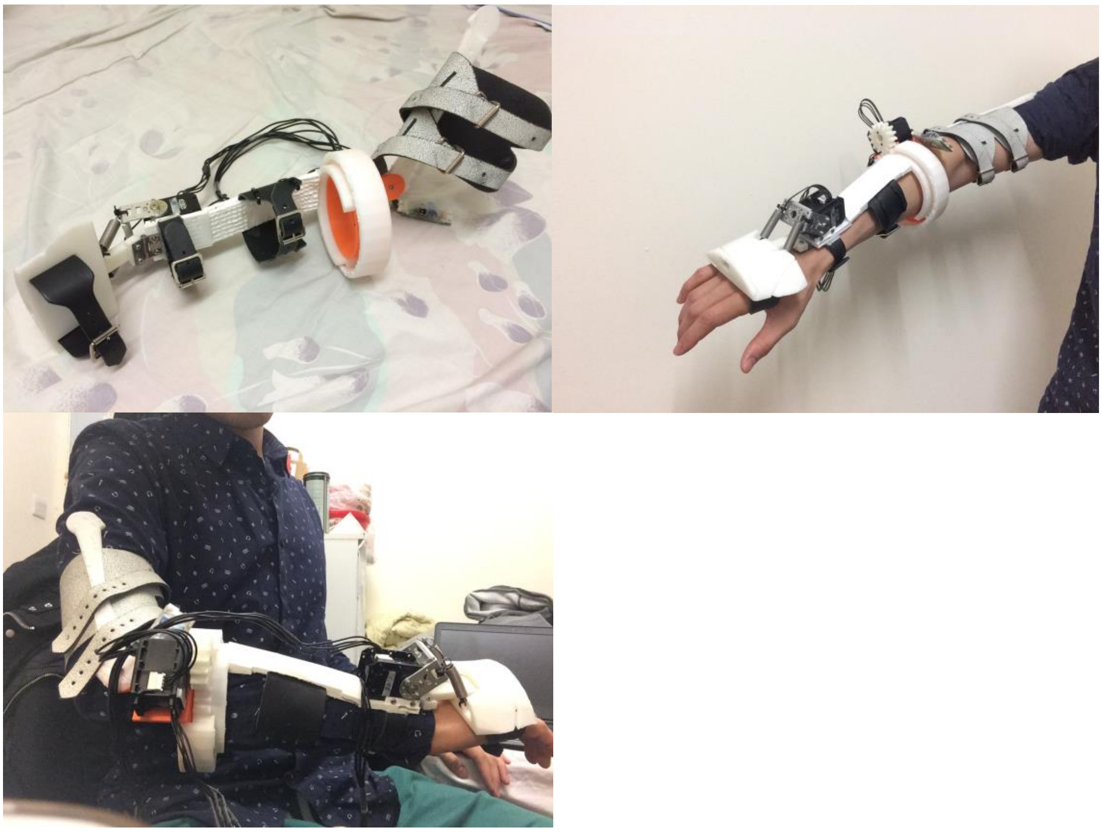


Figure 4.8 Final design and configuration of the wearable robotic device for the tremor control of the upper limb motions: flexion-extension of the wrist and pronation-supination of the forearm.

4.5. Results & discussion

4.5.1 Tremor motion and suppression simulation in rigid frame

The simulated tremor vibrational motion in a frequency about 4 Hz measured and determined by the BSN wireless node system with gyroscope and accelerometer, see Figure 4.3a. As the simulated tremor vibrational motion is in two dimensions that are the rotational motion around Z-axis and X-axis, the raw signal of the gyroscope around Z-axis and X-axis were extracted for the validation. For accelerometer, the acceleration along Y-axis can still be sensitive to the tremor motions around Z-axis, however, the rotational motion around X-axis are not the linear movement in any specific direction in the XYZ coordinate system.

After the other two motors were induced into the system, the amplitudes and the frequencies of the tremorous motion were changed due to the friction from the gears inside the motors. The Figure 4.3b shows the raw signals of the simulated tremor motion from gyroscope and accelerometer with the tremor control system being activated after a period of time, see Figure 4.3b. The raw signals from gyroscope show obvious attenuations in the amplitude, but not in that from accelerometer. The mean amplitude of simulated tremor motion was reduced by around 61.5% when comparing the signal of tremor before and after the suppression control being activated.

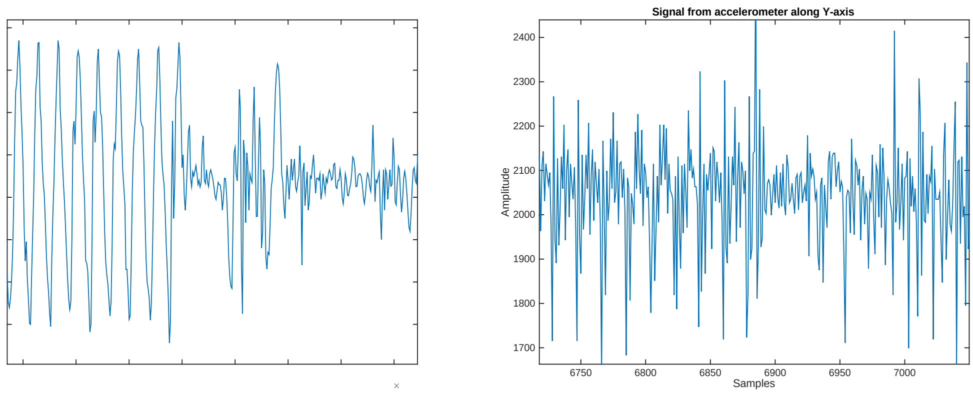


Figure 4.3 Raw signals from a) gyroscope and b) accelerometer before and after the tremor control strategy activated.

4.5.2 Wearable device: Deign and mechatronics

The wearable device prototype was tested by the researcher for the suppressing function and getting feedback and comments from some end users.

The BSN sensor was attached onto the position above the third metacarpal of the hand to record the motion signal from the gyroscope and accelerometer for evaluating the suppression function. Figure 4.5 illustrates the amplitude of the simulated tremor motion from the researcher before and after wearing the device without being activated, and also after the device being activated. The mean amplitude of simulated tremor motion was reduced by around 77% when comparing the signal of tremor before wearing the device and after wearing the device being activated. It is also observed that there is a huge reduction at about 65% in the amplitude even if the wearer is just put the device onto their limbs without activating it. The reason for this can be caused by the geared motors inside the device and the structure of the device. Since there will be damping effect on the motion at the wrist and to the forearm by the geared motors due to the torque ratio that is equal to the gear ratio:

$$R = \frac{T_B}{T_A} = \frac{N_B}{N_A}$$

where R is the gear ratio, T_A and T_B are the input torque to the input gear and the output torque to the output gear correspondingly, and N_A and N_B are the number of teeth on the input gear and the number of teeth on the output gear. The torque generated from this gear ratio applies a damping force to the tremor motion without activating the tremor suppression system.

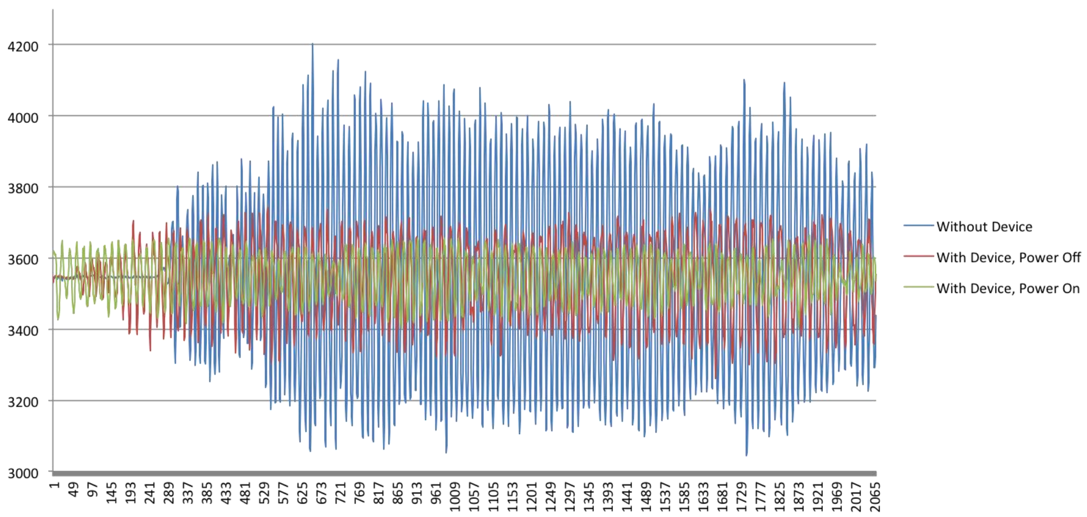


Figure 4.5 Raw signals from gyroscope detecting the simulated tremor motion acquired from the researcher.

Apart from the quantitative approach to evaluate the tremor suppression performance of the device, three end users consisting of two males and one girl age around 30 to 70 with some Parkinsonian tremor were recruited to give feedbacks and comments to the design of the device. Those comments are focusing on the uncomfortable feeling that may be mainly caused by two reason: 1) the pressure in contact area between the limb and the device: since there is only the 3D printed material in contact with the hand and arm of the users, where the material is hard and rigid that will cause high pressure onto the limb when wearing it; 2) the high torque caused by the gear ratio from the geared motor required to do the pronation-supination movement of the forearm.

5. Behavior classification

The wearable robotic device for tremor suppression should be light in weight as the wearer will be using it to assist their activities of daily living (ADL) for a long period of time during the day, and therefore power source for the device is needed to be small in size but have enough power capacity to support the daily use. Power saving strategy is one of the solutions to achieve this goal. According to the daily life behavior of the neural disease disorder patient, the tremor suppression may not be required as there is no intentional motion for important task. For example, tremor could be still occurred as the patient is walking while the tremor suppression is needed when he/she is holding a cup of water or a spoon.

5.1. Feature extraction

After the signals from voluntary motion and tremor motion were decomposed successfully by the previous methodologies in chapter 3, the frequency, amplitude and torque of the tremor motion can be determined and used for the control strategies of the tremor suppression feedback control system in future, while the signals of the voluntary motion can be used for ADL recognition and classification for further investigation of determining the moment of activating the tremor suppression function so as to employ the power saving strategy.

Data collected from the six volunteers were separated into six sets of data for so as to let the machine learning system recognise the behavior of the volunteers being studied. In order to retrieve the useful information from the continuous data sets for behavior recognition continuously, the data sets were undergoing three basic steps: preprocessing, feature extraction and classification.

For the preprocessing step, a segmentation method for time series data “sliding windows” with 70% overlap was used to divide the signal into small time window of

1.6 seconds. With the statistical approach, seven different features for all windows were computed for the classification of ADL, which is commonly used in pattern recognition and machine learning. Those seven features are extracted over the window:

Time-domain

1. Mean: the average value of the signal across the window
2. Standard deviation: the standard deviation of the signal across the window
3. Median: the median value across the window
4. Skewness: the statistical distribution value of all values within the window in terms of steep slow degree,

$$Skewness = \frac{n}{(n-1)(n-2)}\sum_{i=1}^{n}(x_i - mean)^3 / std^3$$

   where mean is the mean of x_i, std is the standard deviation of x_i

5. Kurtosis: the degree of distribution peakedness across the window

$$Kurtosis = \frac{n(n+1)\sum(x_i - mean)^4 - 3(\sum(x_i - mean)^2)^2(n-1))}{(n-1)(n-2)(n-3)std^4}$$

   where mean is the mean of x_i, std is the standard deviation of x_i

6. Q1: the 25th percentile across the window
7. Q2: the 50th percentile across the window
8. Q3: the 75th percentile across the window
9. Inter-quartile-Range (IR):

$$IR = Q3 - Q1$$

   where Q3, Q1 is the 75th and 25th percentiles cross the window respectively

5.2. Classification

Several selected features were used as the input of the activities recognition classifiers for the classification after the features were extracted from the signal. There are different types of most widely used classification methods in previous published literatures. In this study, Naïve Bayes, Bayes Net, nearest neighbor, Random Forest, Sequential Minimal Optimization, Decision Tree J48, Decision table, RIPPER decision rules, Bagging and Adaboost M1 boosting were employed in WEKA environment, data mining open source software (www.cs.waikato.ac.nz/ml/weka/). [133] Apart from Adaboost M1 boosting classifier, where the base classifier was replaced by Fast Decision Tree Learner, default parameter settings are used in all cases. The performance of these behavior recognition classifiers were compared and evaluated. Then a cross validation method was employed to test the models for generalizing the independent data with large amount of features and small sampling size of data. [134] For a k-fold cross-validation, the whole dataset will be divided randomly into k equal size sub-datasets. One of the sub-datasets is then selected to be the testing dataset for testing the model while the k-1 sub-datasets are used to be the training dataset. This cross-validation process will be repeated for k times with each of the sub-datasets being used once as the testing dataset. In this study, 10-fold cross-validation is employed for all the classifications as it is commonly being used in all different kinds of situations.

5.3. Results & discussion

Figure 5.1 shows the accuracy of the classification performance of the activities by ten different classifiers for all six volunteers with the generated feature files from the signal of gyroscope and accelerometer. The average of classification performance using the features from the signal of gyroscope has higher capability to get high accuracy than that from the signal of accelerometer, and even for the activities with simulated tremor motion. Therefore, this suggests using the features from the signal from gyroscope for the activities classification.

Figure 5.2 shows the accuracy, root mean squared error and time taken to build model of the activities by ten different classifiers for all six volunteers with the generated feature files from the signal of gyroscope without and with simulated tremor motion. By comparing the performance of all different classifiers being tested for the datasets without and with simulated tremor motion, Bayes Net, Random Forest, Decision Tree J48, Bagging and Adaboost M1 boosting show a relatively higher accuracy classification, while Bagging produced the lowest root mean squared error during the classification, and Bayes Net classifier build the model in the shortest time. To conclude, Bagging classifier is proposed to be used for the real application of ADL recognition in real time since it can produce a relatively high accuracy classification with lowest root mean squared error in a shorter time than most of the other classifiers.

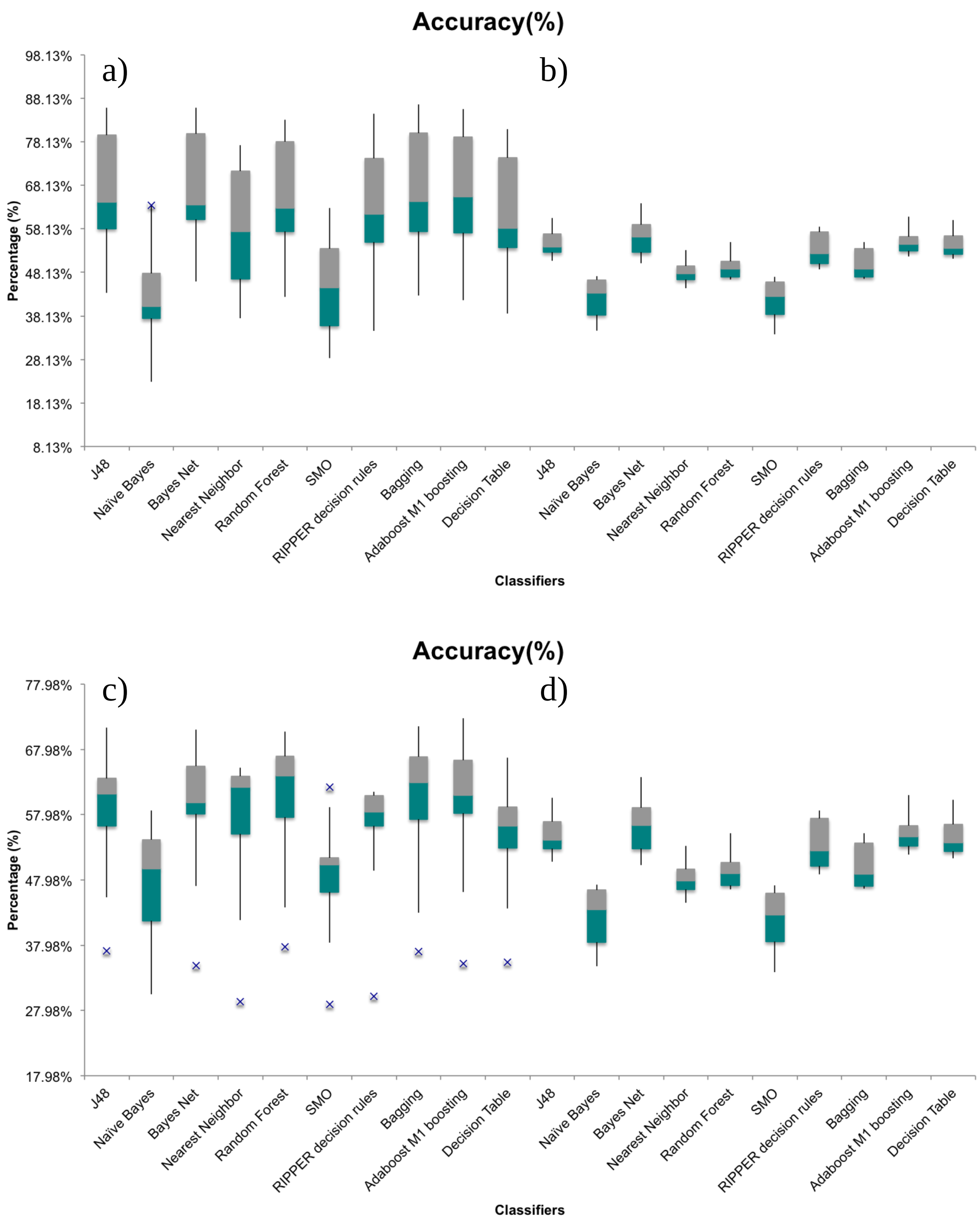
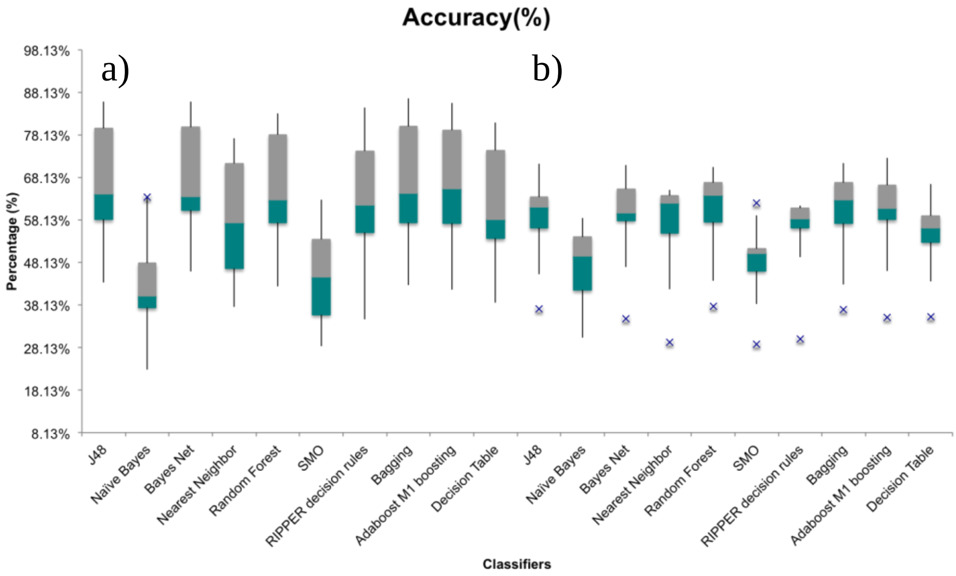
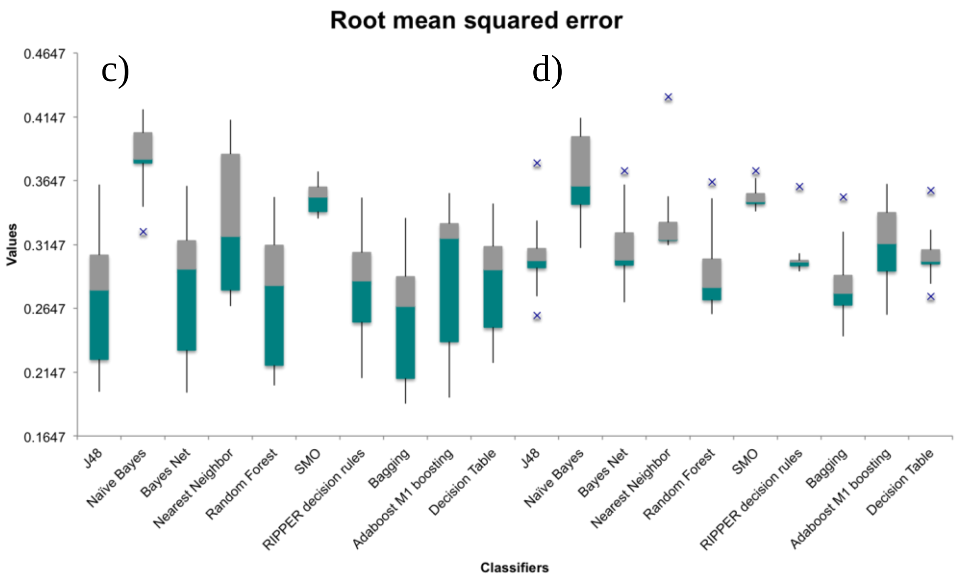


Figure 5.1 the accuracy of the classification performance of the activities by ten different classifiers for all six volunteers with the generated feature files from the signal of a) gyroscope and b) accelerometer, and those from the signal of c) gyroscope and d) accelerometer with simulated tremor motion.


Accuracy(%)
a)
b)
98.13%
88.13%
78.13%
68.13%
58.13%
48.13%
38.13%
28.13%
18.13%
8.13%
Percentage (%)
J48
Naïve Bayes
Bayes Net
Nearest Neighbor
Random Forest
SMO
RIPPER decision rules
Bagging
Adaboost M1 boosting
Decision Table
Classifiers


Root mean squared error
c)
d)
0.4647
0.4147
0.3647
0.3147
0.2647
0.2147
0.1647
Values
J48
Naïve Bayes
Bayes Net
Nearest Neighbor
Random Forest
SMO
RIPPER decision rules
Bagging
Adaboost M1 boosting
Decision Table
Classifiers

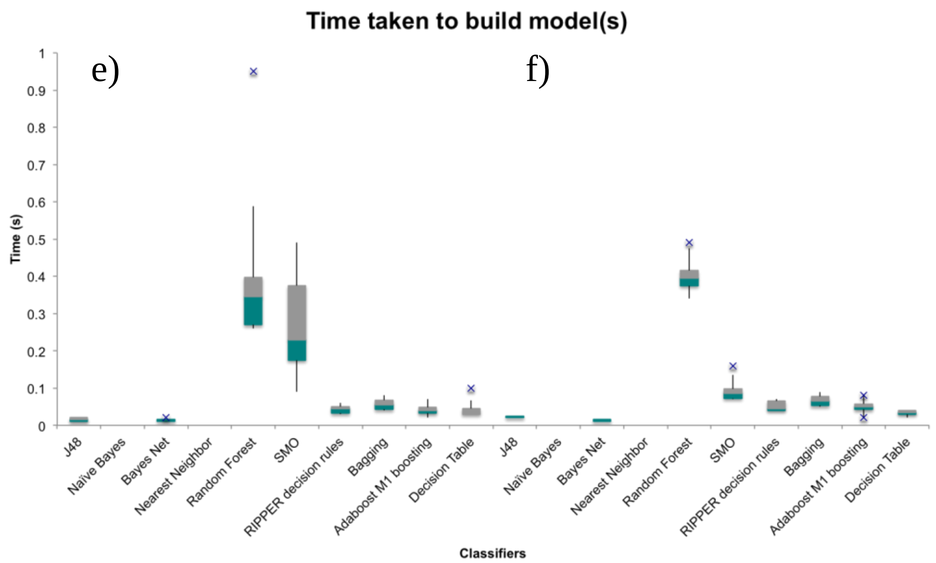

Time taken to build model(s)
e)
f)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time (s)
J48
Naïve Bayes
Bayes Net
Nearest Neighbor
Random Forest
SMO
RIPPER decision rules
Bagging
Adaboost M1 boosting
Decision Table
Classifiers

Figure 5.2 The classification performance in accuracy, root mean squared error and time taken to build model of the activities by ten different classifiers for all six volunteers with the generated feature files from the signal of gyroscope a), c), e) without and b), d), f) with simulated tremor motion.

Figure 5.3 shows the statistical feature distribution for each activity measured by gyroscope is indicated in six different colours with the datasets from all six volunteers. This indicated that nearly most of the feature points from each activity were evenly distributed to all eight attributes, i.e. all six different colours shown in nearly all the frequency histograms. Therefore, that could be the reason to the question why the classification cannot reach to 90% accuracy. Figure 5.4 shows a confusion matrix of the specific classifier validation, which can help explaining more detail about the reason of low accuracy. The data shows false positives for the detection of sit activity, which some of the data are originally belongs to walk, run, point, move bottle, and walk with holding a bottle. This is due to the short period of pause during the whole motion of these activities. Since the gyroscope sensor is used to detect the angular velocity of the hand where it attached in the reference frame of the whole body, the gyroscope will not detect any angular velocity as the hand stop rotating or moving. For example, some of the volunteers may not move their arms as they walked; they hold their arms tight when they ran; they held their arms for a long period of time after stretching out and pointing; their hand did not have any rotation as they were holding the bottle.

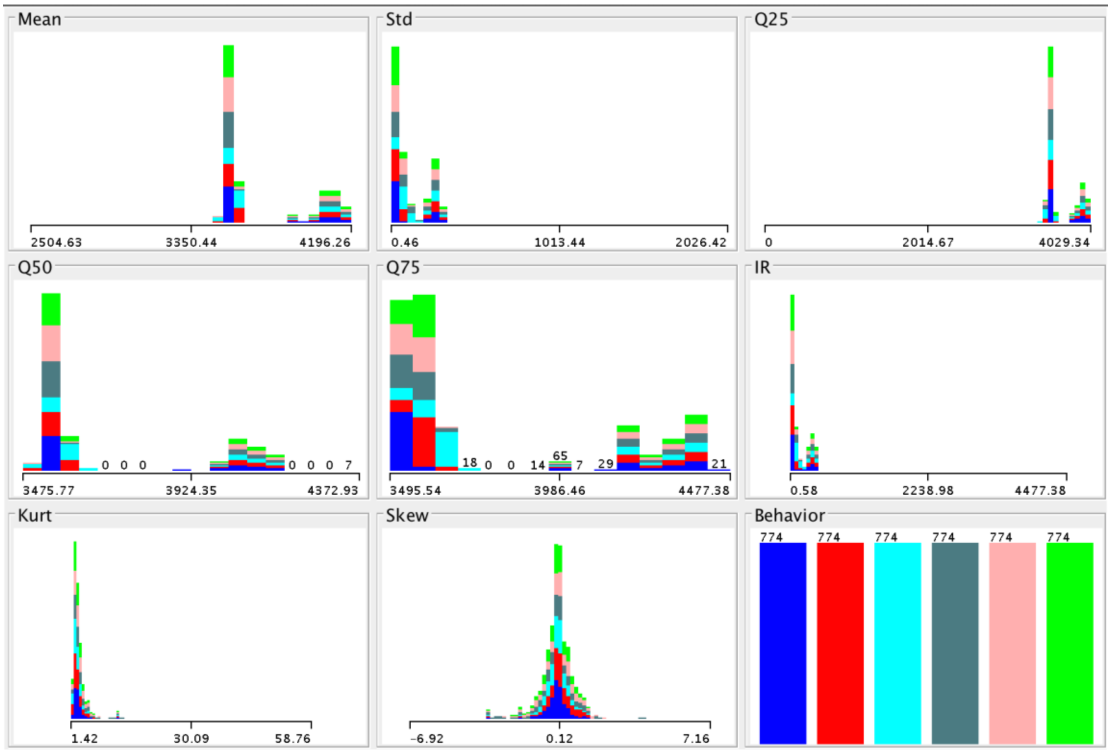


Figure 5.3 The statistical feature distribution for each activity measured by gyroscope is indicated in six different colours with the datasets from all six volunteers.

```
  a   b   c   d   e   f   <-- classified as
689  11   2  15  43  14 |   a = sit
282 306  49  22  70  45 |   b = walk
269  54 349  32  53  17 |   c = run
287  21  46 253 140  27 |   d = point
253  48  20 110 261  82 |   e = move bottle
234  50  10  35 153 292 |   f = walk + carrying bottle
```

Figure 5.4 The confusion matrix of the specific classifier validation for each activity measured by gyroscope with the datasets from all six volunteers (10-fold-cross-validation).

6. Conclusion

6.1. Summary of thesis

A wearable exoskeleton for tremor suppression can be potentially beneficial to patient with Parkinson tremor or Essential tremor in dealing with different activities of daily life due to its lightweight, flexible and multifunctional feature.

This thesis presented a novel design and development of 3D printed tremor suppression wearable exoskeleton, the study and the classification of daily life activities by using the BSN wireless sensor system. The mechanical structure and the working mechanism of the device with the threshold control strategy shows the success in suppressing the tremor motion simulated by a healthy subject, which is evaluated by the measurements of the BSN sensor. With the usage of BSN wireless sensor system, the simulated tremor motion and voluntary motion can be captured and investigated for designing the tremor suppression control strategy. The two methods: a digital pass-band Butterworth second order filter and the Empirical Mode Decomposition (EMD), were used to decompose the raw data into tremor motion and voluntary motion successfully. Also, those datasets captured by the BSN sensor system was found to be useful in the machine learning in recognising and classifying the ADL behavior. The behavior of ADL can be classified into different activities according to the sensor data sets so that the device can choose to turn on or off the power to the tremor suppression system so as to save energy. Furthermore, the classification can also help analyze the tremor motion of the patient like torque, frequency and amplitude of tremor in the relation to different behaviors.

6.2. On-going research and future work

The current design of wearable exoskeleton uses geared motors and rigid material only to evaluate the tremor suppression function. Flexible and soft materials should be used for being the material for the main structure of the device, especially for those areas in contact with the hand and forearm. The geared motors used in the current prototype could be replaced by magneto-rheological dampers. Magneto-rheological damper can provide a more flexible damping effect to the tremor with less effect to voluntary motion. The wearable exoskeleton for tremor suppression with the active actuators (not dampers) can be transformed to the assistance device for providing supportive force to those people with muscle weakness like elderly people for retain their daily life activities.

In the current study, the version of BSN sensor system is limited to use one type of sensors for each measurement. Using next version of BSN system can measure all data sets from both gyroscope and accelerator at the same time frame in order to have more features extracted for enhancing the machine learning classification performance. EMG muscle signals can be captured by a wearable EMG sensor like Myo® armband, see figure 6.1, which has eight EMG muscle sensors and some motion sensors. With the help of EMG signal, the tremor motion can be analysed in the neurological approach. Not only the control strategy can be enhanced by EMG signals for more accurate detection of tremor motion, but also the machine learning classification accuracy can be improved along with the features of the signals from gyroscope and accelerator in the sensor fusion system. Figure 6.2 shows all the eight sets of EMG signals from the Myo® armband for the six activities: sit, walk, run, point, move bottle, and walk with holding a bottle. With the help of EMG signals, tremor motion can be studied in a deeper level by comparing and finding the differences between the EMG signals of normal activities and those with tremor motion. Since the EMG signals consist of eight different channels for each of the activities, the data analysis methodology needs to be redesigned in order to fit for interpreting tremor motion and voluntary motion from the EMG signals.

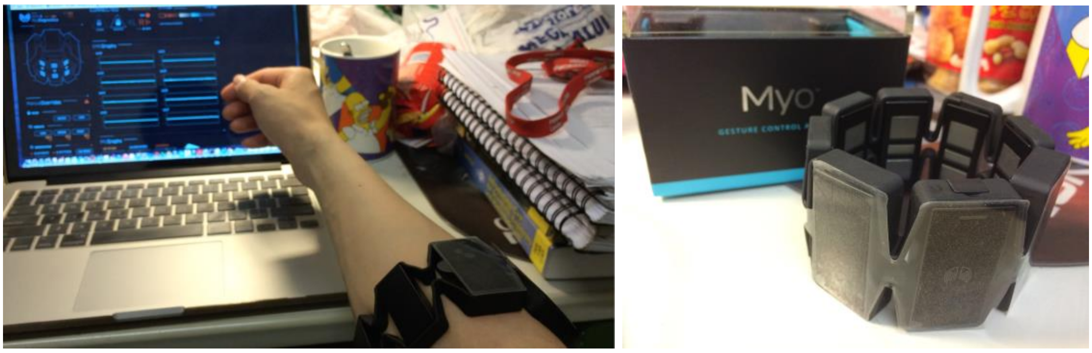
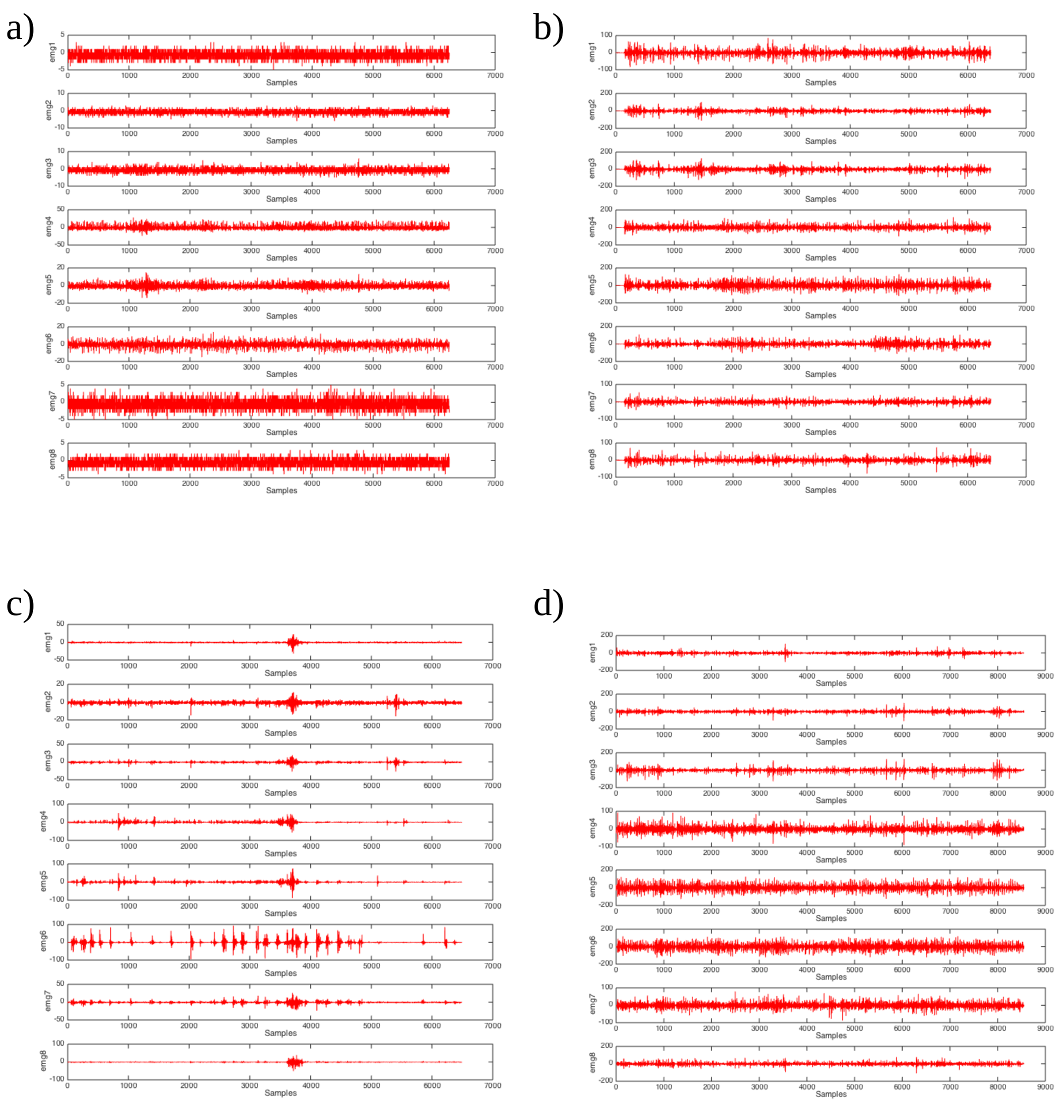
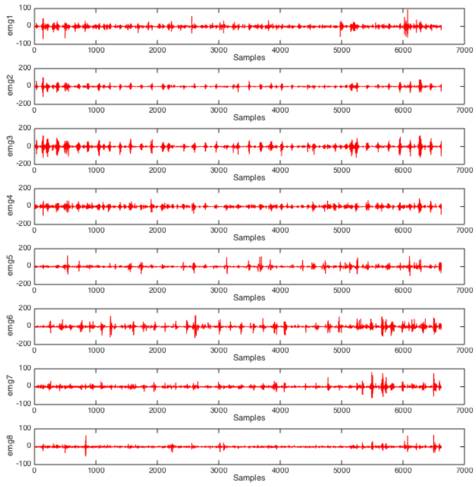


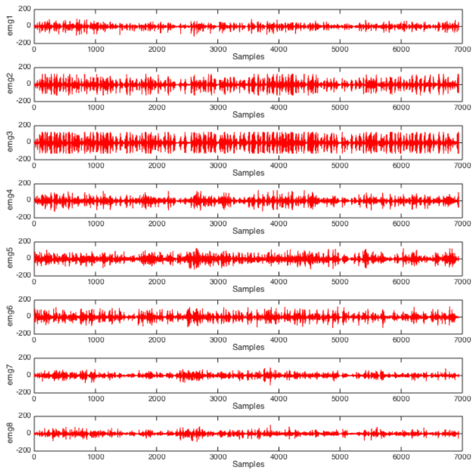
Figure 6.1 Myo® armband has eight EMG muscle sensors and some motion sensors.



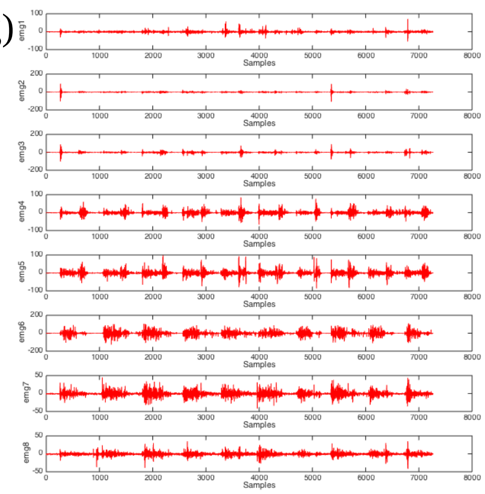
e)



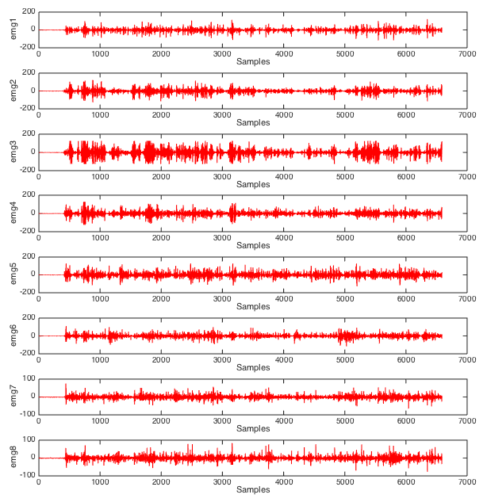
f)



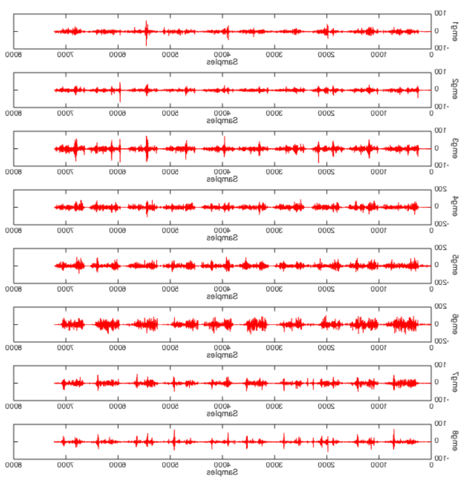
g)



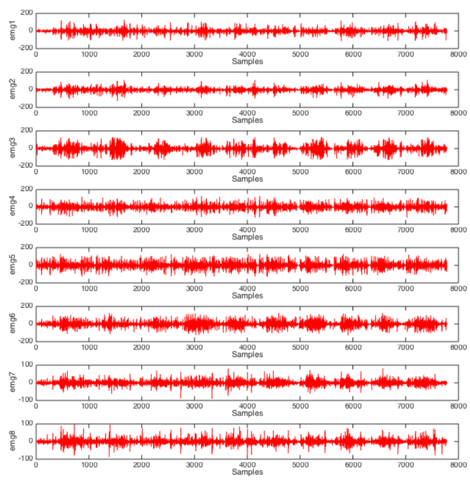
h)



i)



j)



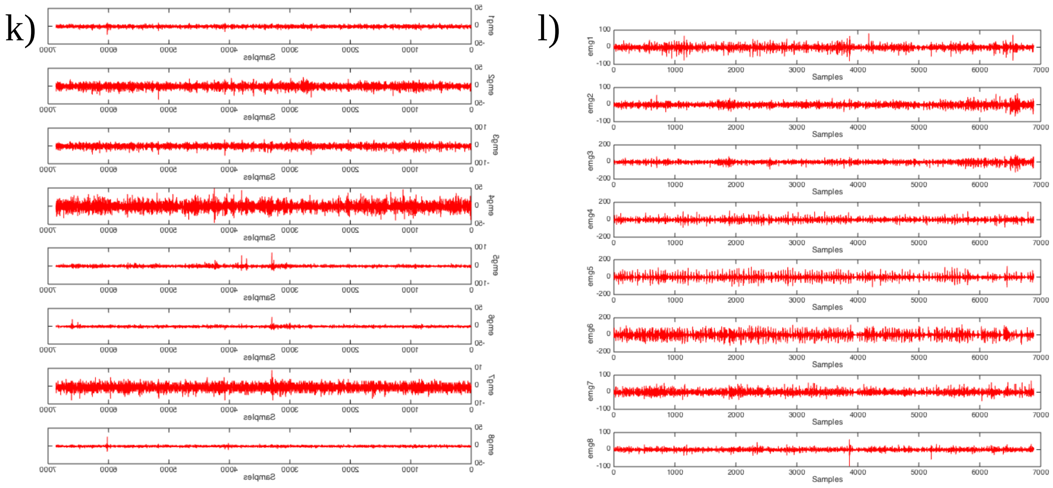


Figure 6.2 EMG signals from the eight EMG sensors inside Myo® armband. a), c), e), g), i), k) refer to the six activities while b), d), f), h), j), l) refer to the six activities with simulated tremor motion.

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