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The Development and Experimental Characterization of a Haptic Feedback Array to Enhance User-Perception of Locomotor Function and Motor Control of an EMG-Controlled Prosthetic Limb

A Dissertation

By

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Abstract

This dissertation presents the development and experimental evaluation of a high-resolution haptic feedback array (HRHFA) for enhanced user-perception of lower-extremity limb function. The HRHFA is comprised of a grid of miniature direct-current vibratory motors contained within a conformable, additively-manufactured harness worn on the user's lateral forearm. A multi-dimensional control architecture was developed to convey kinematic and combined kinematic-kinesthetic sensory information associated with knee function using vibrational stimulations applied along the length of the forearm. Experimental results of the HRHFA with subjects performing level-walking gait demonstrated the ability to enable statistically significant improvements in stride and cadence reproduction, and without the need for collocating the HRHFA with the ipsilateral lower limb. Building upon these results, follow-on experimental evaluations of the HRHFA were conducted for trajectory control of a myoelectric, powered-knee transfemoral prosthesis. When compared with nominal tracking performance (i.e., myoelectric control of the prosthesis with only visual feedback of knee motion), tracking performance with haptic feedback of knee motion using the HRHFA showed significant improvements in tracking error and repeatability, with concomitant reductions in learning times.

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I. Overview

A. Introduction

Lower limb amputation continues to be the most prevalent form of limb loss in the United States. Approximately 2 million Americans are suffering from lower limb loss. Of these limb losses, approximately 25% are due to trauma. The remaining are due to disease-related etiologies. Of these diseases, diabetes and other dysvascular phenomena are the largest contributors. Diabetes is expected to contribute to 58,000 yearly amputations by 2030 (Dillingham, 2008). With the increased incidence of lower limb loss secondary to dysvascular diseases, there is a correlated an increase in unfavorable rehabilitation outcomes. This is likely due to the increase in sedentary lifestyle during the lengthy (median 6 months) rehabilitation process, which greatly contributes to disease progression (Fletcher, 2002; Hordacre, 2013; Stineman, 2009).

Even upon successful completion of the rehabilitation process, locomotor difficulties and their associated secondary effects are not uncommon. The discomfort caused by this is evident in the marked number of amputees who discontinue prosthetic limb use (Roffman, 2014). These locomotor difficulties can be due to a number of issues, chief among them being poor socket interfacing, poor user implementation, and the limitations in functionality of current commercial limb systems. Poor socket interfacing is outside of the purview of this work, but nonetheless is an important factor in proper limb functionality. Poor interfacing is often due to limb volume fluctuations, poor socket fit caused by an improper fitting process, or poor limb alignment, all of which can lead to uncomfortable weight distribution in the socket environment (Cain, 2015). The latter two

problems are often intertwined, with poor limb functionality being a common contributor to poor gait technique. Poor gait technique can include things like vaulting, where the amputee will plantarflex the foot contralateral to the prosthetic in an effort to improve toe-clearance, foot slap, where the amputee forces the foot down defensively to gain knee stability, and others like terminal impact, circumduction, increased lumbar lordosis, lateral and anterior trunk bending, and abducted gait. The common trend amongst these poor techniques is that many of them can become habitual. These poor motor strategies often start during the rehabilitation process when there is some perception of limb inadequacy, either due to actual limb inadequacy stemming from limitations in prosthetic functionality or inadequacies resulting from improper socket interfacing or variances in the level of amputation. While all of these poor techniques are strongly discouraged during the rehabilitation process, many amputees still use them post-rehab for a number of reasons, ultimately leading to the formation of detrimental habitual behaviors that greatly contribute to secondary conditions and limb discontinuation (Cain, 2015).

In an effort to address these rehabilitation shortcomings, commercial innovations have shifted towards microprocessor and powered lower-limb platforms. And though current advances in microprocessor control and powered lower limbs have narrowed the gap between upper and lower limb functional capabilities, a volitionally controlled lower limb prosthesis does not yet exist commercially.

It was proposed that introducing volitional control into the lower limb prosthetic environment could offer an enhanced motor learning experience by allowing intentional feedforward control (Alcaide-Aguirre, 2013), which had already been well-demonstrated in EMG-controlled upper limb technologies (Pons, 2004). The implementation of EMG-

control in a powered transfemoral prosthetic was later investigated, and although the limb was capable of performing on par with current State of the Art (SOA) offerings, there were some deficits stemming from a lack of perceptual awareness for the limb, particularly hyper-extension of the knee upon entering the stance phase and the volitional maintenance of full extension throughout the stance phase (Hoover, 2012; Dawley, 2013). This extension puts undue mechanical and power strain on the limb while also failing to leverage full knee functionality, specifically shock-absorption in stance and the ability to support weight while flexing. From these observations, it was suggested that course control was easy for the user, while fine motor control was more cognitively burdensome (Dawley, 2013). A proposed solution for this perceptual deficit and resultant lack of fine motor control was to incorporate haptic feedback into the volitional control of the powered limb.

The long-term goal of this work was then to further investigate and attempt to remediate the lack of perceptual awareness in an EMG-controlled transfemoral prosthesis. It was proposed that this could be done through the design and experimental evaluation of a novel haptic feedback apparatus, able to provide spatial and kinesthetic information. As the understanding of haptic feedback and its effects on motor control and perception grew, it became clearer that haptic feedback was not only efficacious at significantly increasing the controls acuity of a powered prosthesis, but also capable of tapping into the body's natural perception of autonomous processes. From this enhanced understanding, it was also proposed that the usage of such a haptic feedback suite could greatly reduce the time required to establish proficient control of an EMG-controlled powered-knee prosthesis.

II. The State of the Art in Transfemoral Prosthetics

A. Gait Morphology and Features

Because this dissertation describes human walking gait so frequently, it is important that the fundamentals of human gait are understood. Walking is a highly coordinated rhythmic contraction of muscles that ultimately yields locomotion. Walking is composed of strides, wherein a stride is the completion of one full gait cycle (Figure 1). The gait cycle in its entirety is composed of eight unique phases: Initial Contact (IC), Loading Response (LR), Mid-Stance (MST), Terminal Stance (TST), Pre-Swing (PSW), Initial Swing (ISW), Mid Swing (MSW), and Terminal Swing (TSW). These phases of the gait cycle are further described in better detail below (Perry, 1992). Note that while the ankle provides an important role in able-bodied gait, its functionality is not explored here. This is due to the fixed-nature of the ankle used in this work's powered-knee prosthesis.

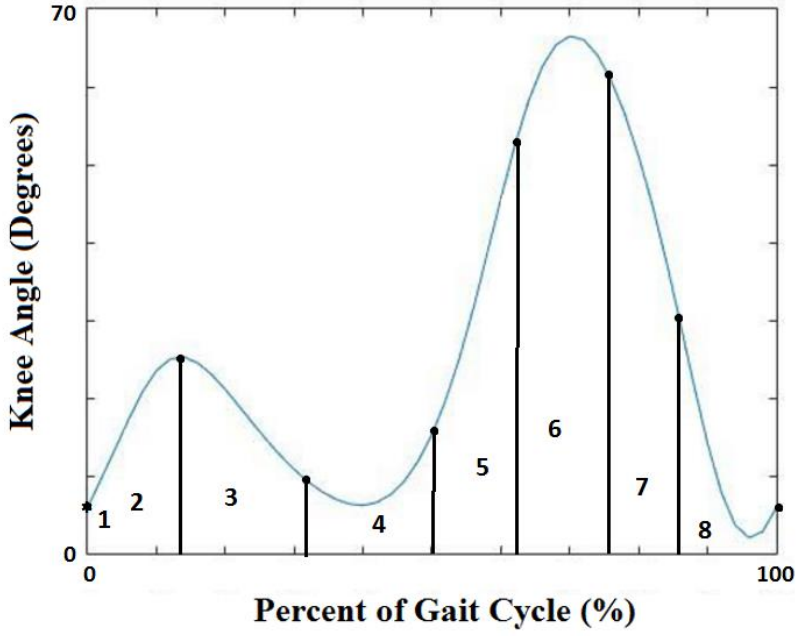

Figure 1: Plot of gait cycle with corresponding morphological features labeled (1-8).

1. **Initial Contact (IC):** Initial contact is the very first instant of the gait cycle (0%), also known as heel strike. It represents the moment in time where the leading foot strikes the ground with the heel. The Knee Angle (KA) during this phase is between 0 and 5 degrees (angles are positive in flexion and 0 degrees corresponds to the knee fully extended).

2. **Loading Response (LR):** The LR constitutes 0 to 12% of the gait cycle during which time the foot is fully planted and the mechanical shockwave is absorbed in the knee and ankle joints. The KA during this phase is between 15 and 20 degrees.

3. **Mid-Stance (MST):** MST constitutes 12 to 31% of the gait cycle. During MST, the knee is approximately fully extended with a KA of 0 to 5 degrees. During this phase, the tibia is gradually moved forward, shifting the center of gravity of the limb while the body is being supported by a single leg.

4. **Terminal Stance (TST):** TST makes up 31 to 50% of the gait cycle. The heel is just lifting from the walking surface and the knee is still fairly extended (0 to 5 degrees), with notable flexion just commencing at the end of TST.

5. **Pre-Swing (PSW):** PSW occurs between 50 and 62% of the gait cycle. The knee is notably flexing during this period, with a KA approaching 40 degrees. This phase is considered complete once toe off occurrs.

6. **Initial Swing (ISW):** Initial swing starts at 62% and ends at 75% of the gait cycle. ISW begins with the toe coming off the ground and the knee angle flexes to a KA of 60 to 70 degrees.

7. **Mid-Swing (MSW):** MSW constitutes 75 to 85% of the gait cycle. During MSW the knee extrends back to a KA of approximately 25 degrees.

8. **Terminal Swing (TSW):** TSW is the final 85 to 100% of the gait cycle wherein the knee is extended to a range of 0 to 5 degrees in anticipation of subsequent heel strike and the restarting of the gait cycle.

B. The Rehabilitation Process

After an individual has had an amputation, they must undergo a lengthy rehabilitation process. The primary objective of the rehabilitation process is to ensure that the amputee develops good prosthetic use habits, which in turn should ensure continued limb use and improved quality of life. The rehabilitation process for a lower limb amputee takes, on average, 6 months (Esquenazi, 2001; Esquenazi, 2004; Dillingham, 1998). A brief outline of the rehabilitation phases are described below (Esquenazi, 2001; Esquenazi, 2004; Dillingham, 1998). This does not include every facet of the rehabilitation process, but gives a good example of the current Standard of Care (SOC).

1. **Preoperative Phase** – This phase's existence is ideal and does not always happen, especially with traumatic amputation that requires emergency surgical intervention. During this phase, the patient is provided information about the amputation process as well as the rehabilitation process. Goals for rehabilitation will also be established and if a long enough time frame can be established, the patient should be started on a cardiopulmonary conditioning program to facilitate the rehabilitation process. In the case of traumatic limb loss, the patient will go through a shortened version of this phase combined with the acute post-surgical phase.
2. **Amputation Phase** – The amputation phase involves the surgical process that ultimately produces limb removal and tissue restructuring.
3. **Acute Post-Surgical Phase** – The acute post-surgical phase begins immediately after the patient is stabilized and out of surgery. This process lasts until the patient is discharged from the acute care hospital setting. During this phase, the objectives are pain control, beginning range of motion exercises, emotional support, education, and functional mobility training. During functional mobility training, the patient will learn how to move around without the assistance of a prosthetic limb. They are trained in the use of wheelchairs and crutches.
4. **Pre-Prosthetic Phase** – This phase generally starts within 6 to 8 weeks post-amputation. During this phase the patient is being prepared for adopting a prosthetic limb. The patient will go through residual limb shaping and stump shrinkage will occur. The patient will be tasked with

learning proper skin care routines because the socket environment can cause disruptive skin conditions when not handled properly. The patient will also work to increase their limb range of motion, muscle strength, and cardiovascular performance. Functional mobility training will also continue during this phase, better teaching the patient how to deal with situations where they may not have their prosthetic limb. Exercises are very important during this phase as this is the time that patients are most vulnerable to loss of strength and range of motion (Esquenazi, 2001; Esquenazi, 2004). Some institutions will begin implementing a practice prosthetic limb during this phase. This is known as an Immediate Post-Operative Prosthesis (IPOP) (Esquenazi, 2001; Esquenazi, 2004).

5. **Prosthetic Prescription and Fabrication Phase** – This phase requires that the patient has a completely healed wound, no notable edema, and a conically shaped mature limb stump. If a patient has developed obesity, it must be well controlled and the patient needs to be under 330lbs. During this phase, a prosthetic limb is prescribed for the patient, they are fitted, and the ultimate limb socket is fabricated.
6. **Prosthetic Training Phase** – This phase occurs around 10 to 11 weeks after amputation. The aim of this phase is to familiarize the patient with wearing a prosthetic limb, increasing the amount of time that the limb can be comfortably worn, and teaching proper weight-bearing and gait techniques. The amount of time that this phase takes is highly variable, but it is generally noted that the more proximal the amputation, the longer time it will take for proper gait training. This is due to the larger amount of

energy required to control the prosthetic limb given what equates to a smaller moment arm.

7. **Community Integration Phase** – This phase comes after successful prosthetic training and seeks to integrate the patient back into their family and community roles. It is particularly important that emotional wellness continues to be addressed and appropriate coping strategies are taught. It is also strongly encouraged that the patient works to resume recreational activities, albeit sometimes in an adapted way.
8. **Vocational Rehabilitation Phase** – During this phase, the patient is assessed and trained for returning to the work-force. This may include building new education goals for the patient in order to take on more appropriate jobs given any disability that may prevent them from resuming their prior vocation. The return to work should be a gradual process that occurs over several weeks with ample counseling and consultation being provided.
9. **Follow-Up Phase** – This is the final and lifelong phase of rehabilitation. The patient should continue to have their prosthetic functionally assessed. Physical and mental health should also be assessed with support provided when needed. A general rule of thumb is follow-up appointments every 3 months for the first year and a half followed by 6 month follow-up appointments thereafter.

Unfavorable outcomes are present in the rehabilitation process, with rates of up to 44% at 1-year post-amputation and 77% at 5-years. While the reasons for unfavorable

outcomes are numerous, unfavorable outcomes can generally be placed into two categories – the inability to return to a good quality of life and mortality. With the ever-growing incidence of diabetes-related amputations, the latter unfavorable outcome is becoming more common (Sauter, 2013). During the lengthy rehabilitation process, the recumbent lifestyle that comes with recovery contributes to the progression of diabetes. The latest statistics show that there is a 5-year mortality rate of 50% associated with diabetic limb loss (Sauter, 2013). Additionally, of this population, 80% can expect a contralateral amputation within 5 years of the first amputation (Sauter, 2013). These patients also often have confounding obesity which further contributes to an inability to become properly rehabilitated due to prosthetic limb weight limits and general physical health requirements for the successful adoption of a prosthetic limb.

Outside of diabetic-related limb loss, other factors exist that can lead to unfavorable outcomes. These usually revolve around discomfort with prosthetic use, improper prosthetic use, or a combination therein. Discomfort stemming from prosthetic use can be caused by improper socket fit or poor prosthetic limb alignment. While both of these problems can be handled by a prosthetist, some patients experience dramatic limb volume changes, making the residual limb-socket interface range from mildly uncomfortable to wholly ineffectual. Commercial options for these patients are limited, but there are suction pumps that work to stabilize residual limb volume and socket fit (Hoskins, 2014). Poor prosthetic limb alignment can occur over time, making the limb uncomfortable and negatively affecting gait. This can be remediated by regular follow-up appointments with a prosthetist. Poor gait habits however, are often much harder to remediate. The number of poor gait habits that can develop over the course of prosthetic

usage are many and varied, but they can lead to prosthetic limb discontinuation because of secondary conditions (Ostler, 2014). These secondary conditions can include chronic back pain and hip pain, which result from constant compensatory motions stemming from improper gait. The best way to treat poor gait habits is through proper training and maintenance of proper prosthetic fit and function. During the rehabilitation process, it is very important that improper gait techniques are identified and corrected. Some poor habits emerge as a result of poor prosthetic fit, alignment, or function. These habits can be corrected by solving these issues with the prosthetic limb (Ostler, 2014).

C. Current Lower Limb Prosthetic Offerings

It is important to understand that there are no volitionally controlled powered knees in commercial existence. Each powered system uses some kind of autonomous or semi-autonomous process wherein the user is often involved but not in direct control of the limb. Commonly used state of the art (SOA) lower limb prosthetics can be divided into two broad classes – microprocessor limbs and externally powered limbs. Limbs explored herein include the Otto Bock C-Leg, Proteor Hybrid Knee, Össur RheoKnee 3, Endolite Orion 3, and the Össur Power Knee.

1. Passive Microcontroller Limbs

The Otto Bock C-Leg is considered by many prosthetists to be the standard of care and is an electronically controlled hydraulic system. The current model is the C-Leg 4, which uses 3-D motion sensing to determine appropriate limb motion. It also possesses an app, which allows users to change limb modes. This allows for different levels of responsiveness ideal for specialized tasks like golfing or riding a bicycle (Otto Bock, 2016). The Proteor Hybrid Knee utilizes a combined pneumatic and hydraulic system

which is controlled electronically. A proprietary, “Reaction force detecting system,” allows for dynamic control of the stance phase. Essentially, the pneumatic unit controls the swing phase while the hydraulic system controls the stance phase. The microprocessor mediates between these modes and sets the pacing (Proteor, 2016). The Össur Rheo Knee 3 uses kinematic sensors to ensure proper stability and dynamic response. It has an interesting feature, wherein the hydraulic system uses a fluid that is viscously variable based on the presence of a magnetic field. This magnetorheologic system purportedly eliminates response delays found in other conventional hydraulic-based prosthetic limbs. The Orion 3 by Endolite is a microcontroller hydraulic transfemoral prosthesis that uses inertial measurement units (IMUs) to convey state information to the limb. These IMUs are not only used to establish gait pacing information, but also for their proprietary enhanced stability performance system which controls trip and stumble-recovery protocols (Endolite USA, 2016).

2. Powered Limbs

The Össur Power Knee is the only commercially available motor-powered knee prosthesis, and it uses sensors to transition between common states required for walking. Specialized states can be induced via specific user-initiated gestures or actions, like turning on exercise mode by extending the limb and pulling on the front toes for 5 seconds (Össur, 2016). Vanderbilt University has also developed a transfemoral prosthesis that combines a powered knee with a powered ankle/foot system. The limb actively powers the knee and ankle joints in response to sensed information at the socket interface and prosthetic foot. User gestures can also prompt the system to modify its functionality, like moving the leg a certain way to enter stair ascent mode (Ledoux,

2015). This limb is currently going through the commercialization process in partnership with Freedom Innovations (Freedom Innovations, 2016).

D. EMG Sensors and Muscle Targeting

Electromyography (EMG) is the process of using electrodes to infer the magnitude of muscular contraction. The ability to interpret muscular activity as a real-time voltage value allows for the direct command and control of a prosthetic limb. This capability has been leveraged for decades in the upper-limb prosthesis industry. It is important to understand the physiological process that occurs within the skeletal muscle, and how it can be converted into an electrical signal. When muscle is stimulated by nervous tissue, a series of events unfold that ultimately yield contraction. This begins with acetylcholine being released into the synaptic cleft of the Neuromuscular Junction (NMJ). Once the acetylcholine reaches the muscle tissue, an electrical potential is created within the tissue. This electrical potential continues to build until it ultimately crosses a threshold. This causes a sweeping cascade effect wherein voltage-gated calcium ion channels open up and calcium flows freely and muscular contraction eventually occurs (Basmajian, 1985).

This process generates a voltage potential that propagates across proximal tissue. This voltage potential can be detected by strategically placed electrodes. If one were to simply place electrodes over a target muscle group, a noisy signal would be observed, like the one shown below in Figure 2.

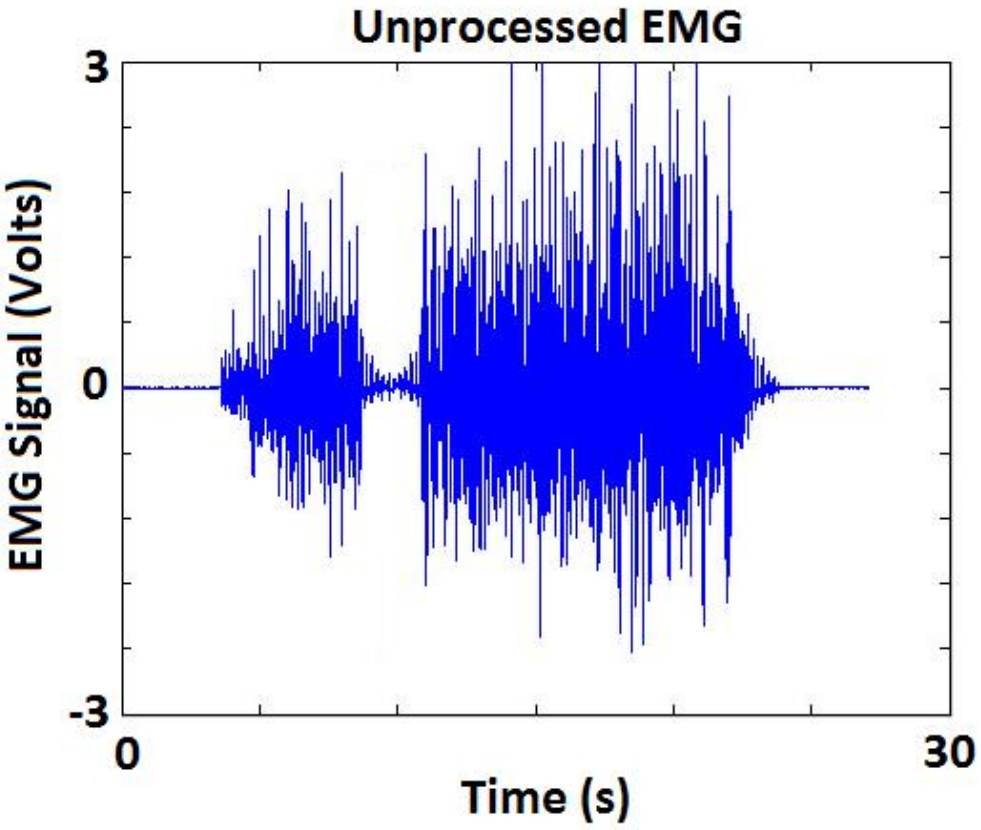

Figure 2: Unprocessed EMG signaling from quadriceps muscles.

This EMG signal can be contaminated from numerous sources including movement artifacts, skin moisture, other muscle signals, and background (environmental) factors. Movement artifacts and skin moisture can be alleviated by better sensor design. Signal contamination from other muscle signals can be avoided by proper placement of the EMG electrode, which will be discussed later. All other noise can be removed via filtering. Filtering for an EMG signal often focuses on creating a bandpass filter from 6 to 600 Hz. This is often done with a high order (around 8^{th}) low pass filter and a 2^{nd} order high pass filter. Note that this filtered signal still isn't very conducive to our purposes of

ultimately controlling a prosthetic limb as it consistently crosses zero and therefore goes between a negative and positive magnitude. This is fixed by rectifying the signal. Now one can observe the filtered and rectified signal of a subject performing flexion (hamstrings) and extension (quadriceps) contractions with their lower limb musculature as shown in Figure 3.

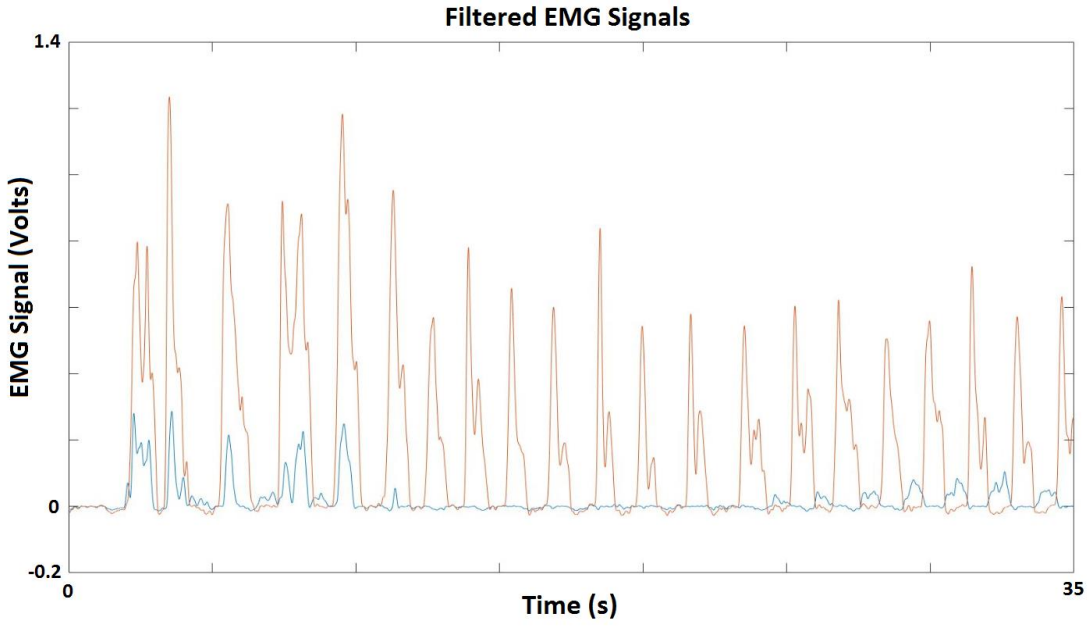

Figure 3: Plot of processed EMG signaling from quadriceps (blue) and hamstring (orange) muscular contractions.

Figure 3 shows the EMG signal in an easier to understand representation of proportional magnitude of muscular contraction - this process has produced what is referred to as the linear envelope. What one cannot tell however, is whether or not other muscle contractions are being picked up in this signal. In an effort to eliminate signal contamination from proximal muscle tissue, it becomes important to understand the basics of EMG electrode placement.

There are two important factors to EMG placement: placement over proper neuromuscular features, and consistency of placement. Each muscle has a unique shape and the way that they are oriented on the body can pose interesting challenges when trying to place an EMG electrode in an effort to detect muscular activity. Because of this, the use of an electromyographer's handbook is strongly recommended (Perotto, 2004). These books offer insight into optimum electrode placement for the desired muscles and muscle groups as well as defining landmarks for the target musculature. When placing an electrode, one should work to locate the muscle through visual inspection first, then manual palpation to locate (approximately) the center of the muscle belly. This is generally the ideal location to place the EMG electrode. It is very important for the sake of reliability and repeatability that the EMG electrodes are placed using the same consistent methodology. Deviation from a consistent placement routine can lead to skewed data. The EMG electrodes used for this work are Otto-Bock 13E202, which are pictured below in Figure 4.

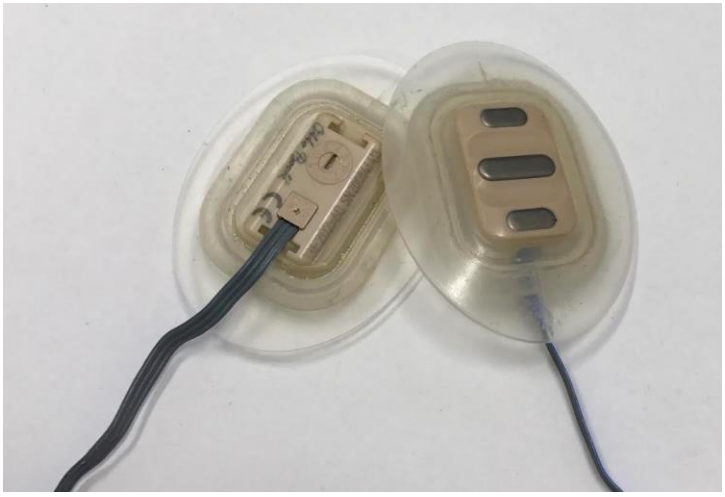

Figure 4: Otto-Bock 13E202 EMG electrodes.

E. Our Prosthetic Limb

The prototype EMG-controlled transfemoral prosthesis, shown in Figure 5, was developed and investigated by Hoover et al. and Dawley et al. (Hoover, 2012; Dawley, 2013).

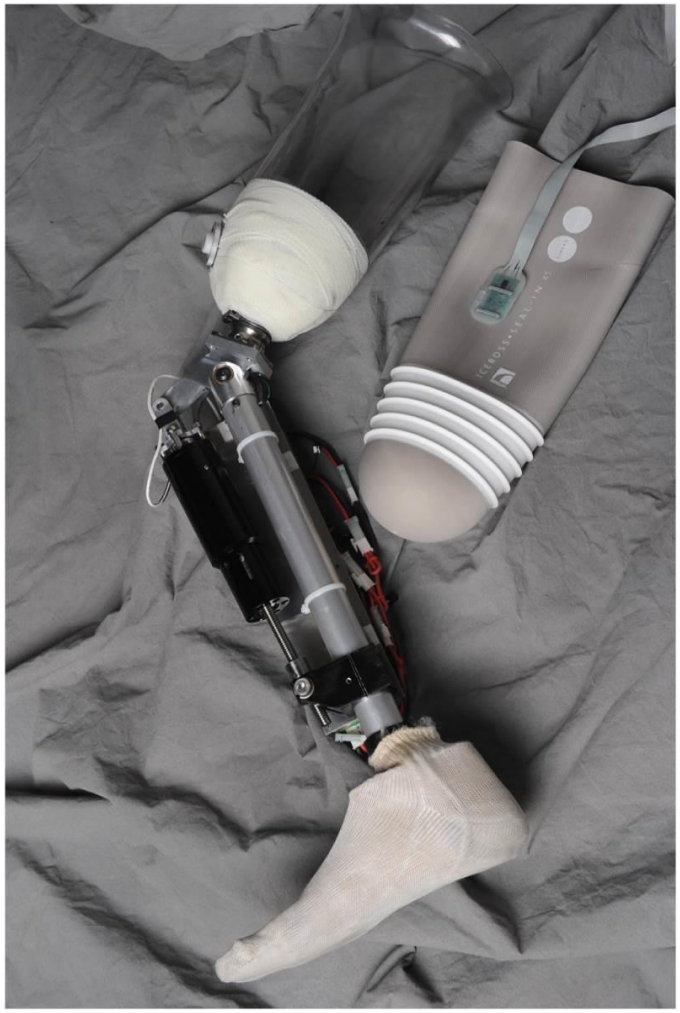

Figure 5: Transfemoral prosthetic leg used for this investigation

The limb possessed a rotary potentiometer at the knee joint, an axial force transducer at the actuator-joint interface, and a pneumatic pressure sensor at the heel and ball of the carbon fiber composite prosthetic foot (Otto Bock Journey 1E44). The knee was actuated via linear actuator consisting of a brushed DC motor (Maxon RE40) and a

ballscrew assembly (Nook ECS-10020-RA). The whole system was powered by custom fabricated lithium polymer battery packs, which supply a combined 48v at 2,000 mAh (12 lithium polymer cells) (Hoover, 2012).

Using a working foundation for the controls, as provided by Dawley et al, the powered-knee prosthetic limb was controlled through a modulation of effective limb stiffness as a function of EMG from two antagonist thigh muscle groups. That is to say, this system offered the EMG control of knee impedance (Dawley, 2013).

A principal component analysis (PCA) was performed on initialization data that is collected under different subject muscle states, like isometric flexion or extension contractions, or muscle rest. The PCA calibration handled co-contraction levels exhibited by the hamstrings and quadriceps, generating effective flexion and extension boundary planes for the EMG signals with a transition boundary describing the radial midpoint between the flexion and extension planes (Figure 6). The boundaries m_f and m_e, that represented flexion and extension respectively, are readily available through the PCA via analysis of the flexion and extension means. The transitional plane boundary, $m_{o,}$ was described by the equation:

$$m_O = tan\left(\frac{tan^{-1}(m_f) + tan^{-1}(m_e)}{2}\right) \quad \text{(I)}$$

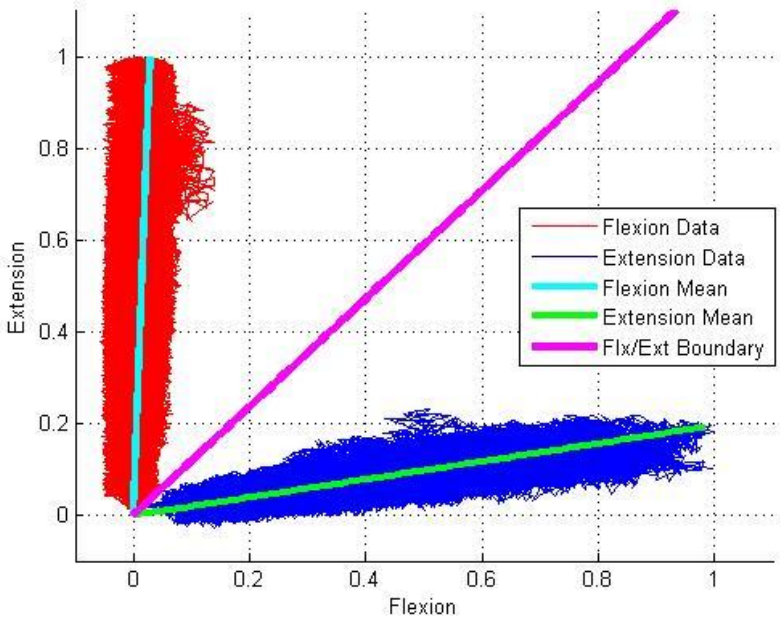

Figure 6: Plot of extension vs flexion data and the established boundary m0 representing the transition between states.

With this EMG signal calibration established, the impedance control architecture for the leg became readily usable. The commanded effective knee stiffness for the powered knee was dependent on the instantaneous, normalized EMG signal inputs, u_e and u_f, again representing extension and flexion, respectively.

$$K = K_{max}\sqrt{u_e^2 + u_f^2} \tag{II}$$

K_{max} was a constant for the leg, representing the effective maximum stiffness of the prosthetic knee. These instantaneous EMG commands were also used to create an effective angular rate of change for the knee that described a desired angular velocity ω_d as shown below.

$$\omega_d = \begin{cases} \left(\frac{m - m_o}{m_f - m_o}\right)\omega_{max} \; if \; m \geq m_o \\ \left(\frac{m - m_o}{m_o - m_e}\right)\omega_{max} \; if \; m < m_o \end{cases} \quad \text{(III)}$$

where:

$$m = \frac{u_f}{u_e} \quad \text{(IV)}$$

From this desired angular velocity of the knee, a desired angular position was computed through numerical integration as follows:

$$\theta_d = \int \omega_d dt \quad \text{(V)}$$

Using equations I-V, the resultant desired knee torque was then given by:

$$\tau_d = K(\theta_d - \theta) - B\omega \quad \text{(VI)}$$

Where θ was the instantaneous position of the leg, ω was the instantaneous angular velocity of the leg, and B was the effective viscous damping about the knee. This control architecture enabled both nonweight-bearing and weight-bearing control and was thus effective for locomotor and non-locomotor functions (Dawley, 2013).

1. EMG-Controlled Powered Knee Prosthetic Experimental Evaluation

The initial in-situ investigation of the above impedance control architecture was conducted by Dawley et al. This investigation involved a single transfemoral amputee subject, who was subjected to varying locomotor tasks in stair ascent/descent and level-ground walking. Overall performance was found to be good, similar to that of current SOA powered limb technology, but there were some noted issues. The user of the limb would command large hyper-extensive knee moments when entering the stance phase of

gait. It was proposed that this hyper-extension is a defensive habit, ensuring that the limb does not collapse during stance phase. Also, the knee exhibited only minimal stance-flexion, yielding reduced shock absorption and increasing hip asymmetry. This defensive technique is not required however, and leads to mechanical fatigue of the limb as well as increased power consumption. It was proposed that this over-torquing of the knee was due to a combined lack of perceptual awareness for the prosthesis and rehabilitative training that encourages more defensive gait techniques, particularly when using a passive limb. It was also proposed that some form of supplemental feedback, i.e. haptic. could remediate this issue by enhancing perceptual awareness of the limb's state (Dawley, 2013). The work presented here details the design and preliminary evaluation of a haptic feedback system for use with the volitionally controlled prosthesis prototype, aimed at ameliorating the aforementioned issues.

III. Haptic Feedback

A. Proprioception and Mechanoreception

Mechanoreception, in summary, is the ability for an organism to interpret and react to some form of mechanical stimulus (Ashmore, 1990). In humans, this is easily recognizable as our ability to perceive touch and pressure, and to perceive the textural characteristics of a surface. When a hand is brushed over something grainy, the nervous system perceives a higher degree of vibration on these surfaces than when hands are brushed against something smooth – like polished glass. When something smooth is touched, like the aforementioned piece of glass, the body perceives the distinct lack of vibration rather than presence of vibration. In more rudimentary organisms, like single cell specimens, the whole cell body can act as a mechanoreceptor, responding to impacts as it travels through various mediums. But humans aren't rudimentary organisms; they are arguably the resultant summation of rudimentary organism components – cells. This summation of components and their corresponding perceptual information is incredibly important to how proprioception is formed.

The body is constantly perceptually experiencing its environment and its physical positioning. Deeper in the body, there exist autonomous mechanosensations of muscles and other deep tissues. All of this mechanosensory information, coupled with information from the vestibulocochlear system, combines into this innate ability to perceive oneself in space. This ability is better known as proprioception.

Though the vestibulocochlear system is undoubtedly important to the development and maintenance of proprioception, its exploration is not pertinent to this dissertation and thus, its exploration will be brief. The vestibulocochlear system works to

establish the body's orientation in space through input from sensory organs in the inner ear. In essence, it describes how the body is positioned with respect to gravity. This sensation is mediated in part by mechanoreceptors inside the ear that are shaped like hairs. Dysfunction of this system can lead to the perceptual experience of vertigo or other experiences of dizziness and disorientation. The mechano-sensory organs work to build on this fundamental orientation template provided by the vestibulocochlear system to now fill in the established spatial axes with the defined physical boundaries of the body. The remainder of the mechanoreceptive organs in the body are responsible for defining this ever-shifting internal and external state of the human body. Mechanoreceptive organs are uniquely divided into two fundamental types, rapidly and slowly adapting. Cutaneously, there are Pacinian and Meissner corpuscles, as well as Merkel disks and Ruffini endings. Deeper in the tissue, there are Golgi organs and muscle spindle fibers, as well as other visceral stretch receptors (Ashmore, 1990).

Pacinian and Meissner corpuscles are both rapidly adapting mechanoreceptors - they will quickly stop perceiving some continuous stimulus. They are also most sensitive to high frequency vibrations, with Pacinian corpuscles most sensitive to frequencies around 250 – 350 Hz and Meissner corpuscles most sensitive to light touch, around 10 – 50 Hz. These receptors are unique because of the corpuscle structures that surround them. These structures envelope the nerve endings in layers called lamellae, much like an onion, building layer by layer into a bulbous encapsulation. Researchers were interested as to the purpose of this structure, and tested them by systematically resecting layers of the corpuscle and subsequently testing the exposed nerve fiber. What they found was interesting, the nerve would no longer function in a rapidly adapting fashion – instead it

would become slowly adapting (the output signal would not attenuate over time). This implied that the corpuscle structure had some kind of role in the rapid adaptation seen in both forms of encapsulated neuron endings. Those researchers were correct, later work did show that the structural deformation of the corpuscle under sustained stimulations allows for the rapid adaptation of the nervous signaling, but they never quite knew exactly why this was (Ashmore, 1990). Other research endeavors looked more closely at re-evaluating what was thought to already be understood of the rapidly adapting mechanoreceptors. Pawson et al found that they could cause a rapidly adapting Pacinian corpuscle to behave just like a slowly adapting mechanoreceptor. They found that by inhibiting GABAergic receptors in the lamellar cells, the cell would not rapidly adapt to a mechanical stimulus. This means that the lamellae were not truly providing a mechanical benefit, as was initially thought. Instead the lamellae of the Pacinian corpuscles have receptors that work to facilitate the rapid adaptation seen in the Pacinian corpuscles via bio-chemical interactions. These research findings were further corroborated by Cabo et al, who further researched the purpose of such GABAergic receptors in Pacinian corpuscles. They believe that the mechanical stimulation of the lamellar tissue could then cause an antagonistic response, which causes the encapsulated nerve ending to rapidly adapt (Pawson, 2009; Cabo, 2013).

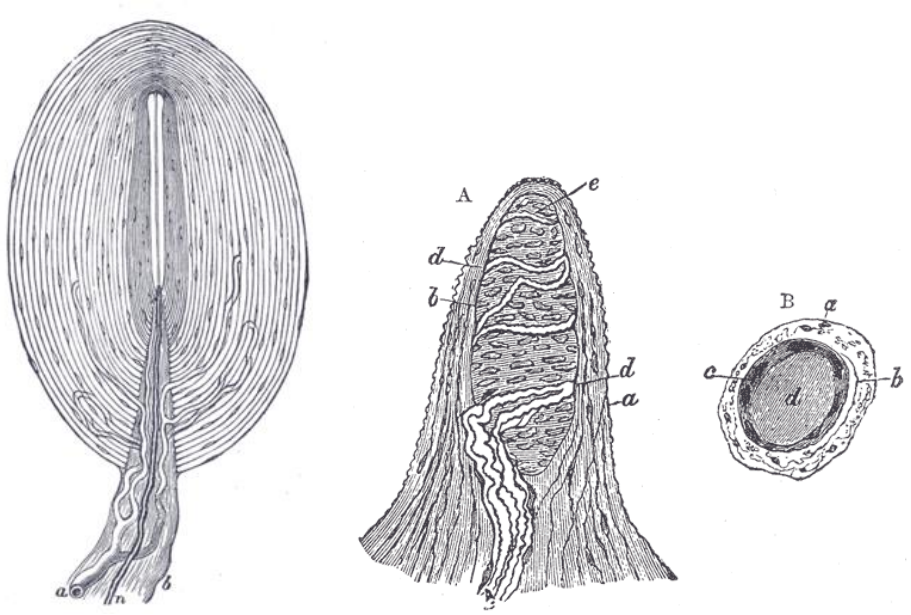

Figure 7: Pacinian corpuscle (Left) and Meissner corpuscle (Right) *Public Domain: Gray's Anatomy*

Because they are most sensitive to vibration, rapidly adapting sensory organs are particularly good at perceiving touch and surface texture. It then makes sense that the most sensitive receptive fields (highest spatial resolution) for these corpuscles would be found in the highest innervation densities in glabrous, or hairless, skin areas – like lips, hands, and feet. This innervation density diminishes almost linearly as one travels medially from the areas of greatest density (Ashmore, 1990).

Merkel disks, which perceive sustained touch, and Ruffini endings, which detect skin stretch, held-object slippage, and sensing/control of finger motion, do not possess any kind of corpuscular structure surrounding their nerve endings. Because of this, they are slowly adapting and most sensitive to lower frequency stimulations. They are particularly sensitive to pressure, and continue to produce a response even when sustained stimulation is applied (Ashmore, 1990). While researchers understood how

Merkel disks and Ruffini endings functioned, they did not understand why an essentially bare neural structure was able to provide slowly-adapting pressure sensation. Through further research, it was proposed that the mechanical stresses put on these nerve endings actuated some kind of mechanically-gated ion channels. With sustained mechanical strain, there would be essentially a continuous stimulation of the neuron, which would imply this slowly adapting behavior. This idea also helped to glean more information on how the corpuscle may work to conform to and comply with a strain, preventing the underlying nerve ending from experiencing a prolonged strain, inhibiting its ability to generate an action potential (Banes, 1995).

Deeper inside the tissue, one would find two very important mechanoreceptors – the muscle spindle fibers as well as the tendon Golgi organ. Both of these organs provide information about muscle contraction and strain at the tendons, allowing the body to perceive the exact spatial orientation of all of its joints. The muscle spindle fibers, also known as intrafusal muscle fibers, essentially act as a differentiator by providing rate of change information for an independent muscle spindle. The summation of these sensory stimuli provide the body with an understanding of muscle change, which inherently allows for some understanding of limb position, limb force and torque (when applicable). This information is complimented by the tendon Golgi organ. This is a stretch-receptor that describes strain in tendons. This proprioceptive information combined with the muscle spindle fibers allows for a complete proprioceptive picture of body position, force interactions, and torque perception. These two mechanoreceptive organs are most important when forming a proprioceptive template of the human body in space.

B. Motor Control and Motor Learning

The human body executes motion through a process known as motor control. Intentional motor control starts with a cognitive desire and ends with a coordinated set of muscular contractions, modulated by sensory input, to yield a desired motion. This motor control processes is essentially a closed-loop control system, wherein sensory input provides feedback required for error correction (Schmidt, 2005; Winter, 2009). There do exist cases wherein motor control would be conducted as an open-loop system, but for the sake of brevity they will not be explored in-depth. The important consideration that has come from research pertaining to open-loop motor control is that fine motor control absolutely requires a closed loop schema (Winter, 2009). That is to say, if perceptual feedback is removed, fine motor control is not be obtainable. This is an important realization when later discussions explore the perceptually deficient interaction between user and prosthetic limb.

While the physiological basis for motor control could be explored ad nauseam, it is more relevant to explore the psychological and learning aspects behind motor control. Motor learning is the process wherein the body changes the motion control of a given motor task in an effort to refine its execution. During this motor learning process, improvements can be observed in motion smoothness, accuracy, and in some instances, the complexity of possible tasks executed (Schmidt, 2005; Winter, 2009). While the increase in motion complexity will not be directly explored in these works, it is nonetheless valuable to state that motor-learning can provide a basis for subsequent motor learning tasks. This could be of particular interest in future endeavors when considering the integration of more advanced powered limb systems.

The motor learning process can be divided into three distinct phases: cognitive, associative, and autonomous (Schmidt, 2005). During the cognitive phase, motion is actively controlled with focus and intention. Because of this, movements are least optimized and will be produced with a lack of fluidity. Errors will be readily apparent in more complex tasks during this phase. The associative phase is when the body begins to optimize the process. There is considerably less focus and conscientious effort in executing motor tasks during this phase. While these motions are becoming more fluid and errors are diminished, discontinuation of learning the task will result in the loss of the skill during this phase. Depending on the difficulty of the motor task, the associative phase varies in length. That is to say, more complex tasks will require a greater amount of time to transition from the associative phase to the autonomous phase. In the autonomous phase, the movement is considered to be highly optimized and there will be permanent memory of the motion. Refinement of controls can continue after this point, but the person does not need to think about the motion.

The autonomous phase is particularly important as the presence of motor synergy becomes apparent. Motor synergy is the physiological process where a task is so neuro-muscularly optimized that the body will dynamically organize – and reorganize - muscle stimulations to offer performance stability. One of the most famous demonstrations of this phenomenon was explored by Nikolai Bernstein, who studied blacksmiths performing a repetitive hammering task (Bernstein, 1967). During his study, it was observed that errors in any given muscle group responsible for hammering were compensated for by the actions of another muscle group. However, Bernstein noted that this was only present in expert blacksmiths, and that novice blacksmiths did not exhibit

this autonomous behavior. This meant that there existed multiple ways for the body to complete a task, or as he described it, redundancy in how autonomous tasks were executed. Nikolai Bernstein proposed that, because the muscle groups were not physically connected, there must exist some kind of learned structure that allows for this rapid improvisation of task execution, dictated by perceptual feedback. He noted that these compensatory adjustments are reflex-like in that they occur faster than perceptual processing should permit, but they are only present in persons who have developed autonomous task performance (Bernstein, 1967). While these observations have been tested and observed by others, the question that still remains is – how is the body storing and optimizing this motion information?

One hypothesis as to the mastery and autonomization of processes is the existence of "motor programs." The ideology of motor programs is that for certain motions, the body stores a motor-control pattern. These patterns can then be combined together into larger permutations of motion. While there have been studies that suggest the existence of such programs, the amount of memory that such a system would consume, just in motor control alone, is prohibitively large (Winter, 2009; Polit, 1979; Grillner, 2005; Shapiro, 1981). Instead, modern research and hypotheses suggest that there exist a finite set of programmed classes of motion, rather than a seemingly infinite set of possible programmed motions (Grillner, 2005). From these classes of motion, and permutations therefrom, one could then construct memorized autonomous motion programs. These could include the hammer-strike motion observed in the expert blacksmith or, more pertinent to the works here, walking.

With these learned motor tasks in mind, it's important to consider what happens when a limb is lost. The body does not immediately disregard all of the proprioceptive and motor control memory that was associated with the amputated limb. This leads to the often-experienced phenomenon of phantom limb pain. Phantom limb pain is the phenomenon wherein the presence of an individual's limb is still perceived. This could range from something innocuous, like one simply feeling as if they can still move their lost limb, to perceptions of an unceasing itching sensation that cannot be scratched, cramping sensations, or burning pain. Because of this, the psychological impacts of phantom limb pain can be profound (Nikalojsen, 2001). Moreover, when learning how to re-use the limb, residual musculature has been configured differently, meaning that the amputee has to undergo a completely new motor-learning process, which can be particularly difficult as subjects increase in age (Alcaide-Aguirre, 2013).

C. Haptic Feedback and Psychophysics

1. Haptic Feedback Background

Haptic stems from the Greek word haptesthai, which means to touch. While this was originally used to define systems that would physically touch a person, it is now used to more broadly categorize any system that offers an augmented perceptual kinesthetic experience. Categorically there are the more common haptic feedback systems that provide touch via mechanical means and then there are more abstract systems like electrical, thermal, acoustic, and magnetic interfaces.

Mechanical haptic feedback devices are most commonly encountered in the form of vibrating motors integrated into cell phones, smart-watches, and video game controllers. While vibrating motors may be the most common form of mechanical haptic

feedback, there are also pneumatic systems that apply pressure stimulus, rotating motors that apply skin-shear stimuli, and linear-displacement (non-pneumatic) assemblies that apply pressure stimuli.

Electrical haptic feedback systems can take on two forms, cutaneous and direct neural integration. Cutaneous electrode implementation creates a unique sensation as small electrical pulses are sent into the skin, stimulating cutaneous mechanoreceptors. Stronger electrical pulses can directly influence deeper muscular tissue, creating muscular contractions as well as more visceral sensations akin to actual limb motion (they stimulate golgi tendon organs and muscle spindle fibers). Extensive work has been conducted in the use of these stronger electrical pulses to generate virtual environments, i.e. a virtual wall that will produce contractions that mimic the sensation of hitting a solid object (Harris, 2016). Direct neural stimulation is also of particular interest to many researchers because it can be used as not only an input for stimuli, but also as a control output for prosthetic limbs. In direct neural stimulation, a surgery is performed wherein a specialized 'nerual cuff' is placed around a target nerve. This cuff has electrodes that can receive and provide electrical impulses directly to and from the peripheral nervous system. While these neural cuffs will be discussed in much greater detail later, their ability to provide an artificial perceptual experience is currently unmatched (Schuettler, 2000).

Thermal haptic feedback devices are not as common in research literature but have been used in applications where low spatial resolution, low frequency, gradated information is being conveyed. Thermal haptic feedback devices have also been used in areas where other mechanical haptic feedback methods are used in conjunction or when

peripheral or central nerve damage has diminished mechanoreceptive capacity e.g. a patient maintains an intact spinothalamic tract (Benali-Khoudjal, 2003).

Acoustic haptic feedback is probably the most variable of the feedback modalities. It can be presented with something as simple as an auditory feedback component (think of the noise a text message makes on a cell phone), to something as complex as targeted-frequency ultrasonic mechanoreceptor stimulation. While auditory feedback is considered by many to be a form of haptic feedback, it will not be considered herein because it does not truly augment the kinesthetic perception of one's environment. Ultrasonic waves, when directed toward muscle spindle fibers and golgi-tendon organs can produce sensations similar to limb motion (Iwamoto, 2001). Preliminary research has shown this kind of intervention to be of use in the rehabilitation process, particularly offering relief of phantom limb pain by providing an artificial sense of the limb (Sherman, 1980). It has also been demonstrated that the same system that stimulates muscular mechanoreceptors can also detect muscular activity in a manner similar to EMG. This is a process known as sonomyography (SMG) and could yield an interesting input-output interface in the near future (Zheng, 2006).

Magnetic or electromagnetic haptic feedback is the most abstract category of haptic feedback devices. By using powerful targeted electromagnetic waves, it is possible to stimulate mechanoreceptive organs non-invasively. This includes deep muscular mechanoreceptive structures, similar to what ultrasonic stimulation can provide (Struppler, 2003). It has been also demonstrated that specialized electromagnetic arrays can provide direct interfacing with the central nervous system, offering the most direct, and non-invasive, methodology for direct neural stimulation (MacDonell, 1999).

2. Haptic Feedback Modality Selection

While there are a plethora of categories for haptic feedback devices that range from commonplace to conceptual, it is important to consider the appropriate devices for investigations with an EMG-controlled powered-knee prosthesis. This section will explore the aforementioned haptic feedback categories, their benefits, drawbacks, and why there were or were not selected for the works presented herein.

Magnetic haptic feedback is the most experimental and while it poses some of the greatest strengths, it has the most prohibitive drawbacks of all the categories. Magnetic haptic feedback is first and foremost prohibitively expensive and must be maintained regularly, which is also costly. Their size and inability to move are also incompatible for use with a prosthetic limb. As these systems continue to be investigated, refined, and scaled down – the possibility of future implementation as human-machine interfaces remains to be seen (Struppler, 2003).

Acoustic haptic feedback is also very experimental, but is more practical and economical than magnetic haptic feedback. The systems are much cheaper and can be portable. But this is portable in the sense that the system is currently the size of a mid-size desktop computer, making them still far too bulky for implementation with a prosthesis. The systems also currently have a prohibitively large power-draw. This system has the most promise however, for future downscaling and implementation in prosthetic technology, since current investigations are being conducted on what are essentially modified ultrasound machines (Gavrilov, 1996). It would not be surprising then to see purpose-built miniaturized ultrasonic devices developed in the next 20 years (Iwamoto, 2001).

Thermal systems are completely non-conducive for use in a prosthetic system. First and foremost, the system response time is simply too slow and the communication of information is nonspecific and unintuitive when trying to communicate something like human gait. Most importantly, amputees often have substantial peripheral nerve damage and poor vascular perfusion – either due to the amputation process or secondary to a dysvascular etiology (McCampbell, 2002). Because of this, there is a greater risk for thermal burning in these subjects making their implementation strongly unadvisable.

Electrical haptic feedback systems have quite a few appealing features. With respect to surface electrode stimulation, the system is very portable, easy to implement in a prosthetic limb, and requires a manageable power-draw. Unfortunately, skin electrodes are not conducive for long-term implementation. It has been shown that prolonged use and development of sweat at the electrode-skin interface will produce an uncomfortable itching and burning sensation that can ultimately produce a contact dermatitis (Kinbara, 2002). This drawback unfortunately excludes skin electrodes since the ultimate desire will be a long-term haptic feedback implementation. Peripheral nervous system implants, or neural cuffs, are much easier to dismiss because of the invasive surgery required and current experimental status of implementation. Another drawback of direct-neural feedback is that scar tissue development has been observed at the electrode interface, which diminishes the efficacy of the system. This scar tissue development requires surgical intervention to re-implant the device, further compounding any secondary risks due to surgery (Polikov, 2005). While the demonstrated performance of direct neural interfaces should not be understated, it is wholly inappropriate for the work presented here.

This leaves mechanical haptic feedback modalities, which offer a plethora of means to stimulate cutaneous mechanoreceptors, each with their own benefits and drawbacks. The most common form, vibrotactile feedback, offers one of the biggest benefits – ease of use. Vibrotactile haptic feedback motors have been continually refined throughout the commercialization process. They are cheap, easy to implement, and have very low power-draw. Drawbacks to vibrotactile feedback stem from the occurrence of desensitization phenomenon, which occurs due to the fact that vibrotactile feedback stimulates rapidly adapting mechanoreceptors, like Pacinian and Meissner corpuscles. This will be discussed in greater detail later. The occurrence of desensitization can be greatly reduced however, with the use of different stimulation frequency-sweeps (Bark, 2008). Because of all the benefits, and the ease with which the drawback can be remediated, vibrotactile feedback was selected as one of the modalities investigated.

Electromechanical linear actuators and skin-shear devices each provide a novel mechanoreceptive stimulus that differs greatly from vibrotactile haptic feedback, and can be designed with power consumption economy in mind. The advantage of these systems is that they target slowly adapting mechanosensory organs, namely Merkel disks and Ruffini endings. The systems that currently exist however, are bulky in design and more difficult to integrate into a compact haptic array. Pneumatic haptic feedback devices can provide both skin-shear and pressure sensations through the use of expandable membranes on the skin surface, allowing for the same advantageous targeting of Merkel disks and Ruffini endings seen in electromechanical systems. These systems have the benefit of being much more compact, but have the significant drawback of requiring both an electrical power source (for the valves) and a gas power source (as the working fluid

for chamber expansion). This drawback was considered more manageable and the use of pneumatic haptic feedback would allow for investigation of both skin-shear and pressure sensations in conjunction with vibrotactile haptic feedback. Because of this, pneumatic haptic feedback was chosen as the second haptic feedback modality to be investigated.

3. Haptic Feedback: Psychophysics, and Learning

While the modality chosen for communicating haptic feedback is an important consideration, it is also important to consider the perceptual experience of haptic feedback. Specifically, it is important to consider how the body understands and interprets haptic feedback and how this can tie into learning. A great deal of work has been conducted in the field of psychophysics to better understand the impact of haptic feedback on perception and learning. This makes sense considering that the field of psychophysics seeks to quantitatively evaluate the relationship between stimuli and the mental processing of such phenomenon (Nevin, 1969).

When considering the contribution that physical stimuli has on motor-tasks, it is interesting to posit how much of a role stimulus plays in performing a basic task. Researchers Jazi et al. sought to answer this question by investigating grasp-tasks (Jazi, 2015). These researchers had participants perform grasp tasks on a piece of fruit, they would then move the fruit to a distance greater than their grasp and ask them to pantomime as if they were grasping the fruit. They found that the pantomime grasp task varied greatly from the actual grasp task, from the actual performance of the grasp approach and the shape of the pantomimed grasp itself. They suggested that this was due to the distinct lack of proper visual and tactile feedback during the pantomime task. In an effort to test this, the researchers set up another experiment wherein the pantomime task

was conducted with both haptic feedback and visual feedback. This time, the pantomime grasp task was significantly more similar to the actual grasp task performance, demonstrating the importance and role of tactile and visual feedback in the initiation and performance of motor tasks (Jazi, 2015). Further expanding on the contributions of haptic feedback to motor function, the work conducted by Yoon et al. explores the effect that haptic and visual feedback have on assistive robotic interfaces. They explored a human-machine interface wherein a user would use a haptic joystick in the completion of a motion tracking task. These researchers found that there was significant improvement in controls and repeatability when only haptic feedback was provided, without visual feedback. While this again states the importance of some kind of tactile perception during the execution of motor controls, the results interject something that seems counter-intuitive. They suggest that haptic feedback alone is better than visual feedback (Yoon, 2017). While this may seem contradictory, it is not altogether surprising when more research work is considered, including research presented herein that suggest visual feedback as a detrimental factor.

When one considers the motor learning process discussed in III.B, where certain motor controls become an autonomous process, it may make sense that visual feedback could negatively impact performance. This could be due to the fact that a visual focus on a task immediately evokes a cognitive-type learning experience. The user is performing a seemingly unfamiliar task and when they are allowed to visually focus, they are overly-cognitive of performance and more akin to make mistakes. When visual feedback is taken away and only haptic feedback is provided, they are less able to be cognitive of the process since tactile sensation seems to be tied to autonomous task-management. This

phenomenon has been further discussed by Ankarali et al. at Johns Hopkins, who also observed this kind of error with a haptic feedback enhanced paddle juggling task. They found that haptic feedback in the absence of visual feedback enhanced the rhythmic performance of the user significantly over visual feedback alone. They propose that such a system has better rhythmic stability because there is a reduction in the cycle to cycle variability that would occur with visual perception and any coinciding attempts to over-correct perceived instability in the system (Ankarali, 2016).

It then becomes interesting to suggest how haptic feedback might interact with learning. If haptic feedback can seemingly communicate with the body's autonomous perception, could it also lead to more intuitive learning? Researchers Neri et al. had a similar question and sought to better understand the ideology behind hands-on learning (Neri, 2015). Neri et al. were motivated by the difficulty in teaching some hard to visualize concepts in their undergraduate physics classes. For this research project, they specifically wanted to better conceptualize and teaching electromagnetism to students. They found that through the use of a virtual reality system with incorporated haptic feedback, students performed significantly better when tested and were better able to depict the three-dimensional nature of electromagnetic fields. The students also stated that the haptic feedback learning experience created a more intuitive understanding (Neri, 2015). Though the researchers don't discuss this further, it is interesting to conjecture that the idea of intuitive learning may stem from the ability for tactile information to better tap into this ideology of autonomous perception. It is then interesting to look a step further at how this could influence interactions with the controls-learning of an EMG-controlled powered prosthetic limb.

The promise that haptic feedback systems show for the rehabilitation process is important and should be considered for enhanced rehabilitation in a smaller time window. However, these systems could also help to dissuade other detrimental effects of limb loss, including phantom limb pain and other psychological comorbidities. The ideology that haptic feedback can help enhance limb ownership while simultaneously lessening things like phantom limb pains has been investigated extensively by D'Alonzo et al., whose most current research has investigated limb-perception with prolonged haptic feedback integration. This work has shown significant improvement in patient mental health while also demonstrating reduced occurrences of phantom limb pain (D'Alonzo, 2015).

D. Research Involving Haptic Feedback and Prosthetic Limbs

The most common commercial implementation of haptic feedback technology is in the communication and entertainment industry. Haptic feedback has proven to be an effective method of alerting cell phone users and creating a more immersive environment for virtual reality and video games. In the field of prosthetic limbs, haptic feedback provides a means for restoring some semblance of limb awareness.

1. Haptic Feedback in Upper Extremity Prosthetic Limbs

This haptic feedback implementation has been extensively explored in powered upper limb technologies. Many researchers have investigated haptic feedback as a methodology to enhance upper limb grasp tasks and to provide object texture information. A smaller subset of these researchers investigated the incorporation of haptic feedback in patients that have received targeted reinnervation (TR) therapy (Bensmaia, 2014). Targeted reinnervation is the process where a select muscle group is surgically denervated. In the upper limb case, these targeted muscles include select groups of the

pectoral and serratus muscles. The ulnar, median, musculocutaneous, and distal radial nerves are then cut at their distal ends and surgically transplanted into the previously denervated muscle tissue. While this work was initially conducted in an effort to enhance sEMG interfacing and allow for a more intuitive control experience for upper limb amputees, Kuiken et al. noticed that some subjects could actually perceive some perceptual abstraction of their severed limb (Kuiken, 2007A). Kuiken et al. continued to investigate this phenomenon which has now led to the modernization of TR techniques that purposely reconstruct the lost limb's perceptual mapping (Kuiken, 2007B; Herbert, 2016).

Brown et al. tested subjects using an EMG controlled gripper that they enhanced with vibrotactile and sustained pressure feedback proportional to grip-force, which they termed force-feedback. These researchers found that the combination of vibrotactile and force-feedback allowed for greater grip management and perception of slip (Brown, 2013). Brown et al. later created an EMG-controlled powered manipulator for use in able-bodied individuals. This system was enhanced with joint-force feedback and vibrotactile feedback. They again found that force-feedback is an effective way of inciting proper magnitudes of grip forces (Brown, 2015). Christiansen et al. tested an EMG-controlled grasping task while using haptic feedback in the presence and absence of visual feedback. They found that the incorporation of haptic feedback showed significant improvement in controls when deprived of visual feedback. The haptic feedback also enhanced the user-perceived performance of the grasp tasks when provided visual feedback (Christiansen, 2013). Aziziaghdam et al. applied haptic feedback to the clavicle in an effort to provide material stiffness characteristics. These test subjects were

able to successfully distinguish a sense of softness and hardness of items that they could not see and accurately sort them from softest to hardest (Aziziaghdam, 2014). Treadway et al. used an EMG-controlled manipulator which was subjected to a random antagonistic driving signal. The error signal was conveyed via a pressure haptic feedback cuff. Haptic feedback allowed the users to effectively manage a steady state, despite the antagonistic signaling (Treadway, 2015). Van der Riet et al. sought to create a low-cost prosthetic hand that could rival current State of the Art (SOA) models. They found that the inclusion of haptic feedback greatly enhanced the functionality of their economical hand design, which totaled less than $1,000 (Van der Riet, 2015). Behbahani et al. experimented with the use of haptic feedback as an object-shape communication system. With this haptic feedback schema, these researchers successfully demonstrated that users were able to explore and accurately identify objects with a manipulator while being deprived of visual feedback (Behbahani, 2015).

Kim et al. experimented on amputees that had undergone TR therapy, seeking to investigate how multiple haptic feedback devices could affect the EMG control of a powered upper limb prosthesis with a specific focus on grasping. The work of Kim et al. uncovered limitations to the discernible complexity of haptic feedback inputs, wherein their subjects could not discern simultaneous shear and pressure sensation (Kim, 2012). Gibson et al. investigated the use of auditory feedback in TR patients as a means of avoiding perceptual deficits caused by neuropathy, with an improvement in performance observed (Gibson, 2015). Rombokas et al. used vibrotactile feedback on TR patients to improve performance in the manipulation of virtual objects via force-motion tasks (Rombokas, 2013). Herbert et al. used intraoperative somatosensory evoked potentials on

individual fascicles of the median and ulnar nerves to target specific sensory fascicles that – when rerouted – would allow for targeted percutaneous haptic stimulation of a reconstructed hand map in a transhumeral amputee. This TR therapy led to the successful restoration of haptic perception of the individuals hand and enhanced EMG control of dexterous tasks (Herbert, 2014).

Transcutaneous electrical neural stimulation (TENS) is also a current field of interest when considering haptic integration with prosthetic limbs, but it has a few problems that will be discussed later (de Castro, 2010; Pamungkas, 2013; Tan, 2014). While it is desirable to avoid the issues that come with TENS, electrical stimulation still provides sensations that are most biologically analogous to the original sensory perception. Because of this, implantable neural-interfacing technology continues to be the holy grail of perceptual restoration. Researchers like Tan et al. have been working on chronic implantable nerve cuffs, which are multi-contact cylindrical electrodes that are implanted around peripheral nerves. These have been shown to possess stability for at least a year and are reliable. While these invasive methodologies carry their own sets of risks (drive-line infection, surgical complications, and a need for surgical re-intervention), they have shown significant restoration of a perceived hand-map of the lost limb. As one would expect, the hand-maps that are restored are not the same for all persons, with some individuals perceiving more or less spatial information of the hand than others (Tan, 2015; Schiefer, 2015). The randomness with which the hand-map of the subject is restored shows that a great deal of research still remains; to better understand neural pathways and optimum ways to provide sensory information directly to the brain. Clark et al. have conducted similar work with the Utah Slanted Electrode Arrays

(USEAs), aiming to provide high resolution data input and output via peripheral nerve interfacing, and have found similar results to Tan et al. (Clark, 2011). Some researchers like Normann et al. seek to communicate directly with the cortical structures of the brain via implantable electrode arrays. This research is the most experimental and poses tremendous risk to the patient. Because of this, much of the research is conducted on animal test subjects with promising results showing that it is possible to communicate directly with the brain via implantable electrodes (Normann, 2007).

2. Haptic Feedback in Lower Extremity Prosthetic Limbs

In the lower limb environment, few researchers have explored the use of haptic feedback to provide kinesthetic feedback. Fortin et al. developed an event-based methodology for conveying vibratory characteristics of foot-ground interactions in an effort to convey high resolution terrain information to lower limb amputees. Their test subjects were able to accurately discern multiple surfaces and characteristic features; they are currently working on a high resolution prosthetic-skin interface (Fortin, 2014). Fan et al. investigated the use of silicone bladders to convey foot-ground interactions to the users of a passive transtibial prosthetic limb. They found that this system could reliably convey kinesthetic information (Fan, 2008).

The original study that spearheaded the use of TENS in prosthetic lower limbs was conducted by Sabolich et al. in 1994. In this study 24 subjects were chosen, 12 transfemoral and 12 transtibial amputees. They were asked to walk with and without a TENS system in the socket environment. The system would convey an electrical signal whose strength was proportional to the forces encountered at sensors placed on the plantar region of the foot. Sabolich et al. noted significant improvement in gait symmetry

when the system was used (Sabolich, 1994). Continued research in this field has shown its usefulness as a haptic feedback methodology, but many issues arise with the TENS interface. A combination of sweat and prolonged usage often leads to considerable discomfort and skin damage, which are both highly undesirable (de Castro, 2010; Pamungkas, 2013; Tan, 2014).

Not only could haptic feedback help to provide artificial limb perception, allowing for enhanced daily use, haptic feedback has been shown to be effective in the rehabilitation process as well. Fu et al. have demonstrated that the usage of vibrotactile feedback in the socket of lower limb amputees allowed for better weight bearing technique during the rehabilitation process. The use of such a system to communicate proper and improper weight bearing technique was also found to significantly reduce the rehabilitation time (Fu, 2014).

E. Haptic Feedback Integration with Our Powered Limb System

1. Knee Goniometer

Previously in our lab, a knee goniometer was constructed to allow for the analysis of limb motion performed by able-bodied test subjects or the sound limb of amputee subjects. It is composed of an adjustable scaffold that possess a rotary potentiometer located at a central hinge. The two distal ends possess formed attachment plates that can be affixed to the proximal thigh and distal ankle via Velcro straps. In this study, the knee goniometer was used to allow test subjects to complete motion tracking tasks with the use of their sound limb.

2. One Degree of Freedom Step-Wise Motion Tracking Task with EMG-Controlled Powered Transfemoral Prosthesis.

The discoveries and conjecture that came from works by Dawley et al. lead to the investigation of integrating haptic feedback into the control of a powered transfemoral prosthesis. The haptic feedback arrays shown in Figure 8 were designed for this testing. One array consisted of an aluminum pressure vessel with three chambers that could be pressurized with CO_2 via actuation of Lee Valves model LHDA 242321 microfluidic solenoid valves attached to a Beswick low-pressure regulator and 16g CO_2 cartridge. When these chambers are pressurized, a silicone membrane covering an orifice expanded into the skin interface, imparting a pressure sensation at frequencies less than 10Hz, ideal for targeted stimulation of Merkel disks. The second array was 3D printed using ABS where three Precision Microdrives PicoVibe 12mm vibrating motors were suspended in silicone-filled sockets. The vibrating motors were actuated at a frequency of approximately 250 Hz, ideal for stimulating Pacinian corpuscles.

Figure 8: (Left) Quasi-static pressure feedback array. (Right) Vibrotactile array.

These two haptic feedback arrays were affixed to test subjects as shown in Figure 9 and used to help subjects navigate a non-weight bearing one degree of freedom stepwise motion tracking task. These tasks were conducted with and without visual feedback, and with and without haptic feedback. The haptic feedback system would tell

test subjects to flex (proximal tactor), extend (distal tactor) or remain within a nominally tuned error-band (middle tactor). An example of each possible test configuration (excluding the control test) is shown in Figure 10. During the control test, subjects had a knee goniometer affixed to their sound limb and they were tasked with following the desired trajectory, yielding the best possible performance for the subject.

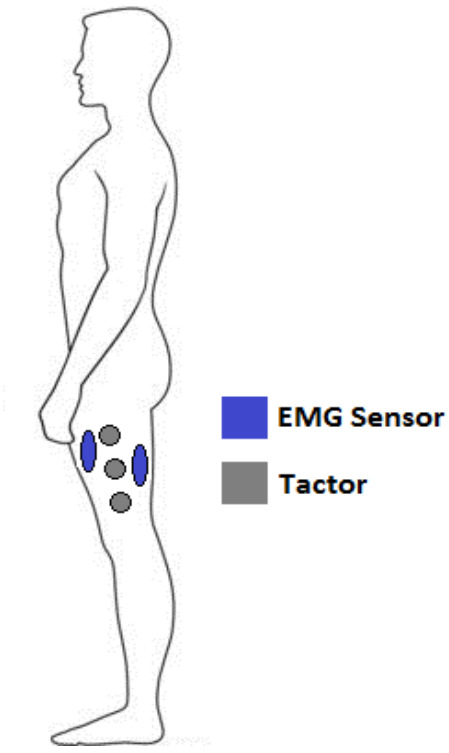

Figure 9: Placement of EMG electrodes and tactor array on test subjects.

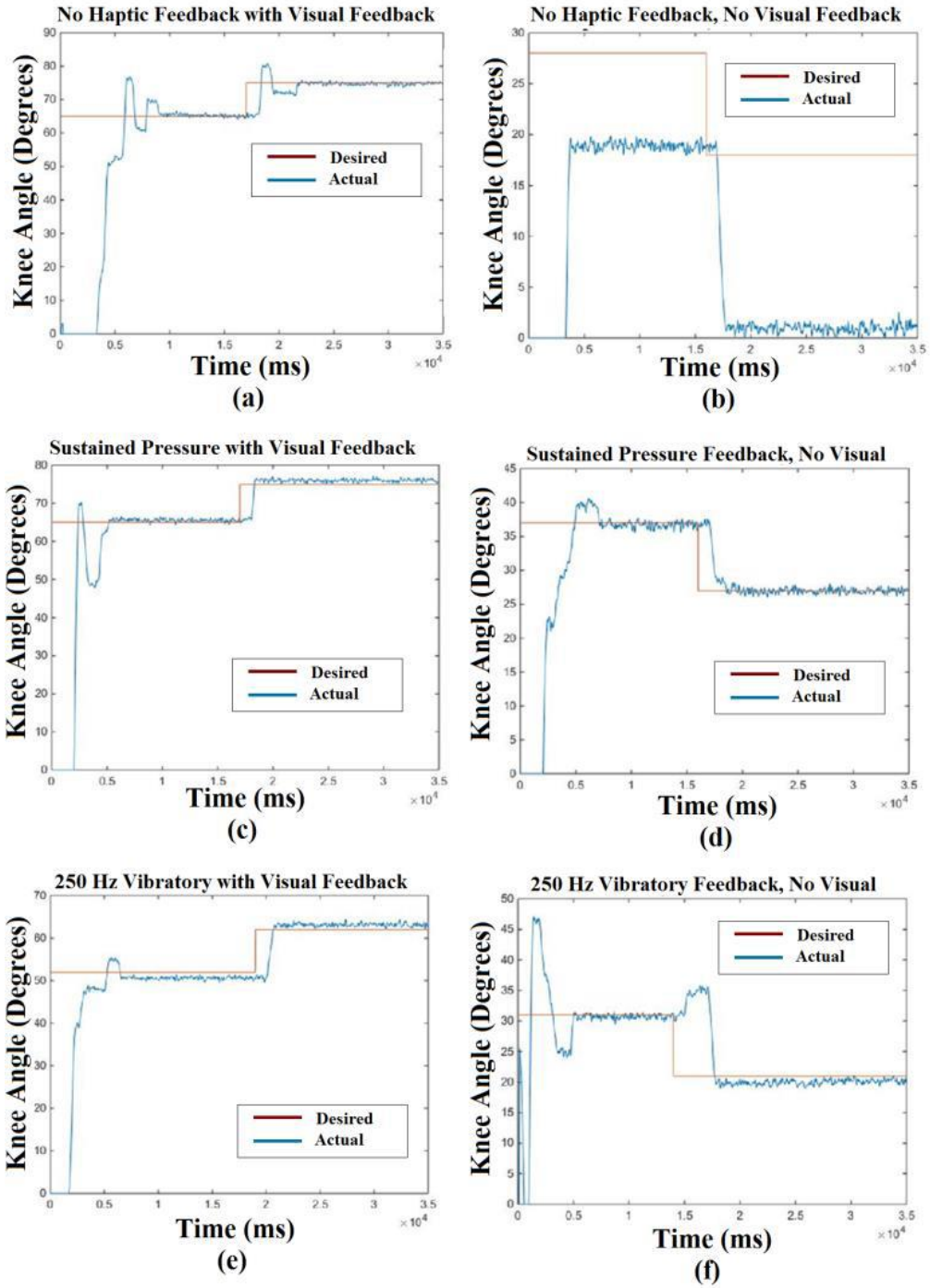

Figure 10: Test showing motion tracking for (a): visual feedback without haptic feedback, (b): no haptic feedback, (c): sustained pressure and visual feedback, (d): sustained pressure without visual feedback, (e): vibrotactile and visual feedback, and (f): vibrotactile without visual feedback.

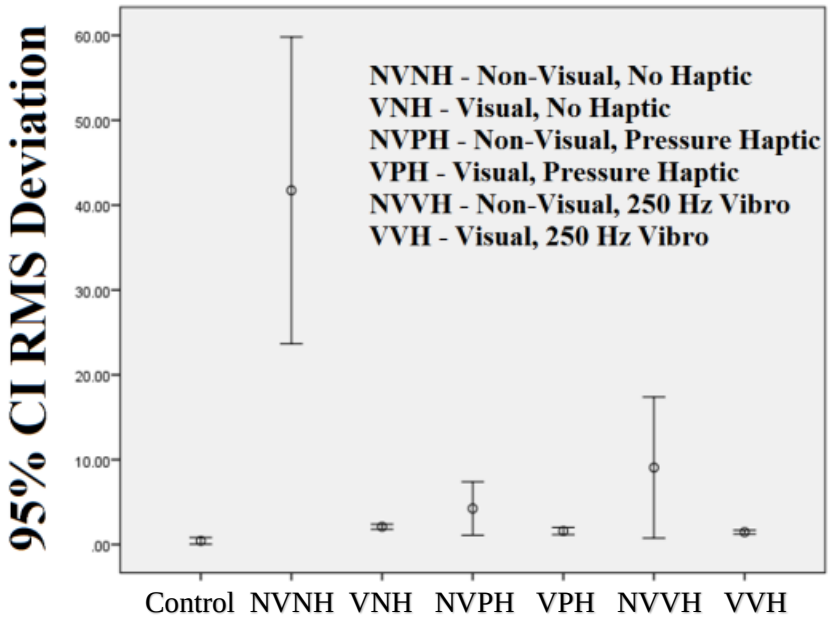

Figure 11: Plot of combined RMS data means for all subjects and all tests

The results of these initial tests showed that haptic feedback significantly improved the control of the powered transfemoral prosthesis, particularly when deprived of visual feedback. These results are best shown by the plot of averaged Root Mean Squared (RMS) deviation in Figure 11 (Canino, 2016A). While these results were promising and gave a glimpse at some of the benefits that could be gained by incorporating haptic feedback into the powered prosthetic system, there were a few questions that needed to be answered with subsequent work. The first question pertained to the desensitization phenomenon that occurred during testing. The effects of desensitization can be seen in Figure 11, where the variance for the vibrotactile testing is higher than the corresponding pressure testing. It became important to better understand and implement measures to dissuade desensitization phenomena. The second question

that arose was whether or not the first haptic feedback system had reached its communication capacity. The system only presented three possible fields of stimulation and thus a low spatial resolution. It was desired to understand whether or not more tactors would yield a higher perceptual resolution. The final question came from qualitative observations during the study, wherein test subjects would learn quickly how to use the haptic feedback system and would develop control strategies to leverage the haptic input. It was predicted that this observed learning behavior would become more pronounced as haptic communications became more complex and rhythmic in nature.

IV. Design and Experimental Validation of Preliminary Haptic Feedback System

A. Design Considerations and Specifications

While the haptic feedback research presented in III.E.2 demonstrated the efficacy of the haptic feedback array in following one degree-of-freedom stepwise-motion tracking tasks, it was desired to show whether or not the array was efficacious in the following of more advanced rhythmic trajectories, i.e. sinusoidal motion or human gait. Given the limited spatial resolution of the array, the most important design considerations were less about the amount of information that could be communicated and rather the most efficient way to convey complex information. This led to the development of a rhythmic feedback architecture that would better convey sinusoidal data.

B. Feedback Controls Development

The haptic feedback systems were actuated via digital output from a National Instruments PCI-6036E interface card installed in a laptop PC running MATLAB Real Time Simulation (rtwin). The redesigned control scheme would transition between three possible feedback states which would utilize the randomly generated sinusoid's phase shift and frequency content. The first feedback scheme was a pacemaker, which would be selected if the user was performing within the constant of accuracy, an empirically tuned boundary layer around the desired trajectory that is dependent on the frequency of the generated sinusoid (Canino, 2016 C).

$$C = \pm Gf \tag{VII}$$

Where C is the constant of accuracy, G is the gain, and f is the frequency of the generated trajectory. This was done to provide a larger margin of error at higher frequency trajectories, since the interruption of these high frequency patterns with error-based feedback proved detrimental to performance in preliminary experimentation. In this pacemaking scheme the user would be provided with a pattern of ascending and descending stimuli *ie.* tactors 1→2→3→2→1, which would follow the generated trajectory at a pace of 5 actuations per period, extrapolated from the frequency data provided. This trajectory would start on either tactor 1, 2 or 3, depending on the amount of phase shift of the sinusoid. Tactor 1 worked to denote the trough region of the sinusoid, 2 denoted the mean value of the sinusoid, and 3 represented the peak region of the sinusoid. This pace-making pattern would ultimately have an actuation pattern consistent with the latter section of Figure 12 (b). If the subject shifts outside of this constant of accuracy, the pattern will immediately transition to one of two corrective feedback states. These two error feedback states will actuate tactors 1→2→3 in the downward (distal) direction or 3→2→1 in the upward (proximal) direction at an increased activation rate per period, which is dependent on the frequency, to communicate desired flexion or extension respectively. Note that the inclusion of a frequency dependent actuation rate for the corrective logic was implemented in an effort to better impart the directional sense of required correction, particularly at lower frequency sinusoids where a slow corrective logic would not be helpful and at higher frequencies where too rapid of a corrective logic would not be discernible. This corrective logic rate can be described by the equation:

$$R = K2^{(M/f)} \tag{VIII}$$

where R is the new rate, K is the nominal pacemaking rate (5 actuations per period), M is another empirically tuned variable which is divided by the frequency, f. A visual representation of these corrective patterns is shown below in the early portion of Figure 12 (Canino, 2016 C).

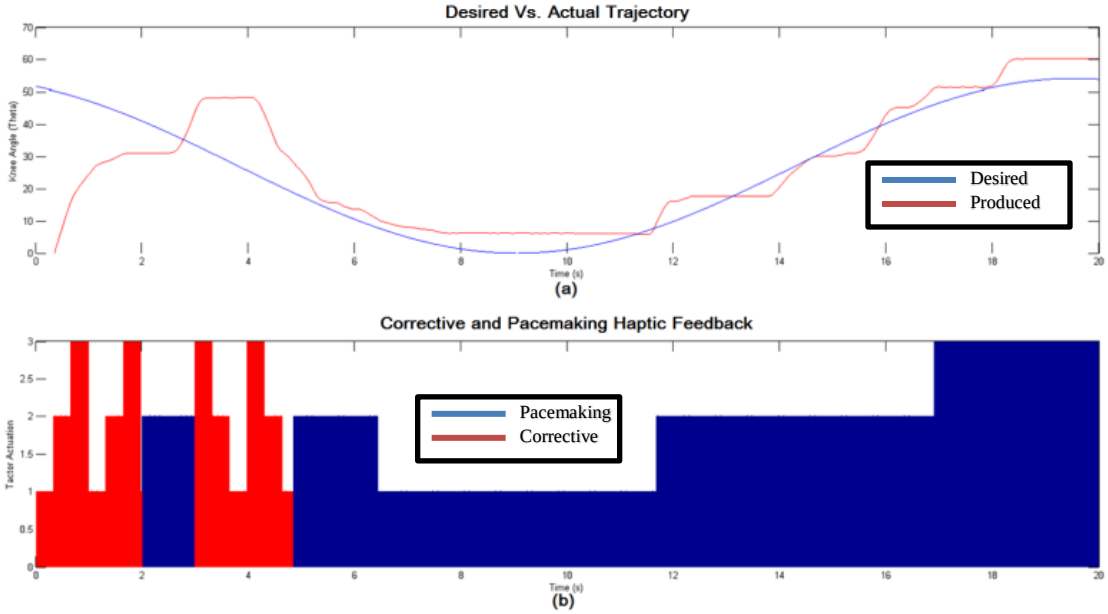

Figure 12: (a) A sample trajectory of the desired vs. actual knee angle. (b) The corrective stimulation pattern in red and the pacemaking pattern in blue. The subject overshoots the desired trajectory initially, transitioning from the flexion-corrective pattern to the pacemaking pattern and then to the extension-corrective pattern before the subject finally settled within the constant of accuracy and followed the pacemaking pattern.

C. Test I: Haptic Feedback in Sinusoidal Motion Tracking

1. Purpose and Background

The success of testing presented in part III.E.2 motivated further refinement of the haptic feedback system as detailed in IV.B. This refinement was done in an effort to better understand the complexity of motion tracking tasks that could be communicated via haptic feedback while still yielding accurate tracking. Randomly generated sinusoidal motion trajectories were selected for these complex tasks. Pseudo-random sinusoidal trajectories were used for these experiments. These trajectories were band-limited about

their offset, frequency, and amplitude. The mean value of the sinusoid was constrained between 30 and 50 degrees, the frequency was constrained between 0.05 and 1.5 Hz, the amplitude was conditionally constrained between 10 and 40 degrees, unless this randomization would bring the waveform outside of the mechanical limits of the knee, in which case it would re-randomize until valid.

2. Protocol

This experiment was conducted using 3 informed and consenting able-bodied adults, one female of age 20, one female of age 28, and one female of age 21. This experiment was conducted under Clarkson University IRB approval # 14-34. These three subjects conducted 6 of each possible test presented in Table 1, leading to a total of 42 data sets.

Table 1: Matrix of all test configurations.

Haptic Feedback Type	Visual Feedback Type
None	None
Static Pressure	None
Vibratory	None
None	Visual
Static Pressure	Visual
Vibratory	Visual
Control	Control

This testing sought to investigate the efficacy of haptic feedback interventions in the accomplishment of significantly more complex non-weight bearing One-Degree of Freedom (1-DOF) motion tracking tasks in the presence or absence of visual feedback.

Initial testing began with the seated subject undergoing the initialization routine outlined in II.E. After initialization, the subject were trained using the limb while still in a

seated position. They were first allowed to investigate how their muscular contractions would affect the dynamics of the limb. After a sufficient acclimation period, the subject was then tasked with moving the limb to different specified knee angles, using a foam rod to indicate desired spatial locations. After 30 minutes of this, they were provided a dynamic knee-angle regulation task where the desired position was changed every 5 seconds. This process was repeated, with 5-minute breaks required after every third 35-second task, in between tasks, the limb was reset to a state of full extension. This whole training routine lasted approximately two hours.

On subsequent testing days, the test subjects repeated the initialization and performed the control study. In the control study, a knee goniometer was affixed to the subject's dominant leg and they were tasked with following a randomly generated sinusoidal trajectory that they could see graphically represented on a monitor in front of them. After this motion tracking task was complete, the subject would be randomly tested in the same fashion as the control test, but they instead used the EMG commands to control the powered limb until one of each test (Table 1) was completed. During this testing, the subject may have one of the haptic feedback systems affixed to them. In which case, the feedback array was affixed to the lateral side of their dominant thigh, with the tactors extending distally from the greater trochanter of the femur via a Velcro harness. Similarly, visual feedback could be provided or denied depending on the test configuration, and the subject was provided a visual representation of their current limb position overlaying the desired limb position via a MATLAB-based Graphical User Interface (GUI). If visual feedback was inactive, the subject did not have the luxury of seeing where the limb was relative to the desired trajectory. Otherwise, subjects used the

haptic feedback cues (if provided) or guessed if both visual and haptic feedback were inactive. It is important to note that subjects were also denied auditory feedback when testing with visual feedback restricted in an effort to prevent them from hearing the powered limb move and using that to unfairly perform well. This was done by having the subjects listen to a white noise track via a pair of noise-cancelling headphones.

3. Analysis

The efficacy of haptic feedback to communicate information pertinent to completing a 1-DOF motion tracking task was investigated using one-way Analysis of Variance (ANOVA). There were 7 possible tests, each repeated 6 times (N=42). Two analyses were conducted, one analyzing the normalized RMS deviation. This was done to compare how well haptic feedback could convey amplitude information. The other analysis investigated the correlation between the two waveforms to observe the accuracy in following the desired frequency. This was done by performing a fast Fourier transform (FFT) to establish the frequency of the generated trajectory, and to also establish any lag between the user input and the generated trajectory. Each trajectory was shifted accordingly and data points were removed from the front and back of both sets to make them even and properly aligned. The sets were then analyzed for their Magnitude-Squared Coherence (MSC) at the generated trajectories desired frequency (Kay, 1988; Rabiner, 1975; Welch, 1967).

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \quad \text{(IX)}$$

where MSC uses Welch's averaged modified periodogram method to estimate coherence between two signals with $P_{xx}(f)$ and $P_{yy}(f)$ being power spectral densities and $P_{xy}(f)$ being the cross-power spectral density. The independent variable for ANOVA was then the possible test configuration while the dependent variables being independently investigated are the aforementioned normalized RMS error and MSC.

The MSC data was found to pass the test of homogeneity of variance while the RMS error data was not. Subsequent investigation found that the RMS error data was robust enough through the Brown-Forsythe test. Multiple comparisons were conducted on both dependent variables, with Tukey HSD being used for the MSC data and the Games-Howell multiple comparison being used on the RMS error data due to its failure to possess homogeneity of variance but still being robust enough for continued analysis.

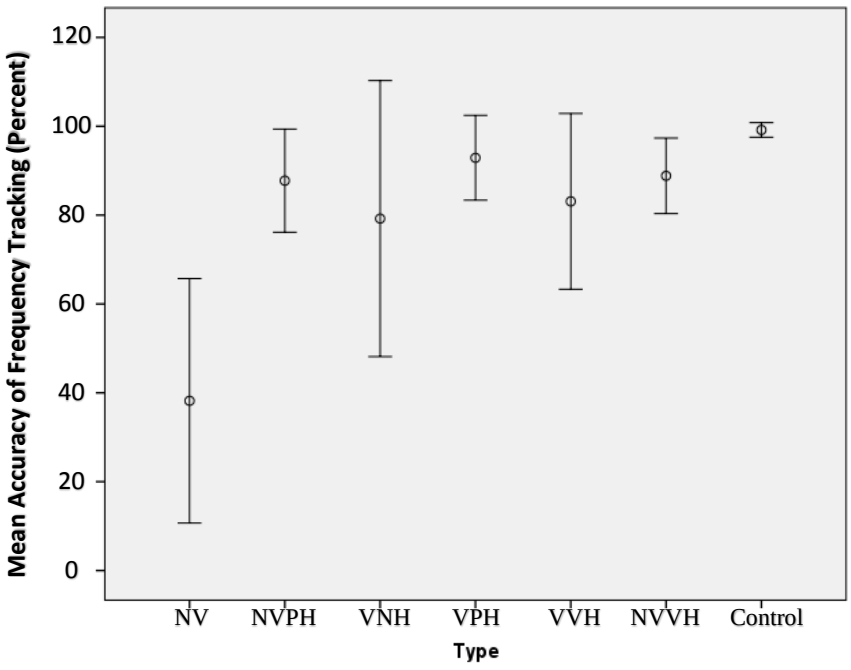

Figure 13: Plotted mean data of frequency accuracy with error bars for the following tests: NV – Non-Visual, No Haptic; NVPH – Non-Visual Quasi Static; VNH - Visual, No Haptic; VPH – Visual Quasi Static; VVH – Visual, Vibrotactile; NVVH – Non-Visual Vibrotactile

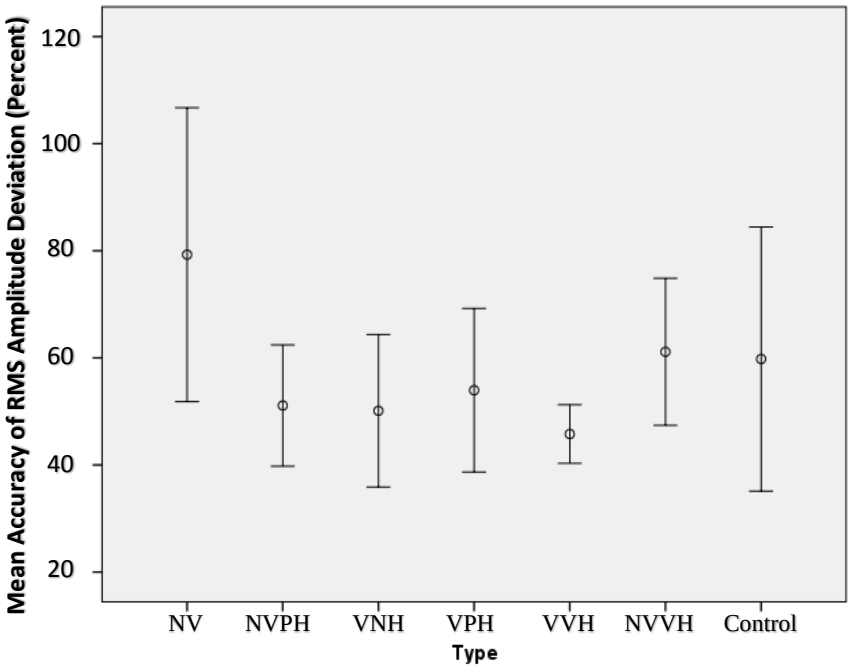

Figure 14: Plot of mean amplitude normalized RMS deviation with error bars for the following tests: NV – Non-Visual, No Haptic; NVPH – Non-Visual Quasi Static; VNH - Visual, No Haptic; VPH – Visual Quasi Static; VVH – Visual, Vibrotactile; NVVH – Non-Visual Vibrotactile; Control – Control Test

4. Results

In Figure 15, there are six presented examples of subjects' individual attempts at the motion tracking tasks, for each of the non-control configurations.

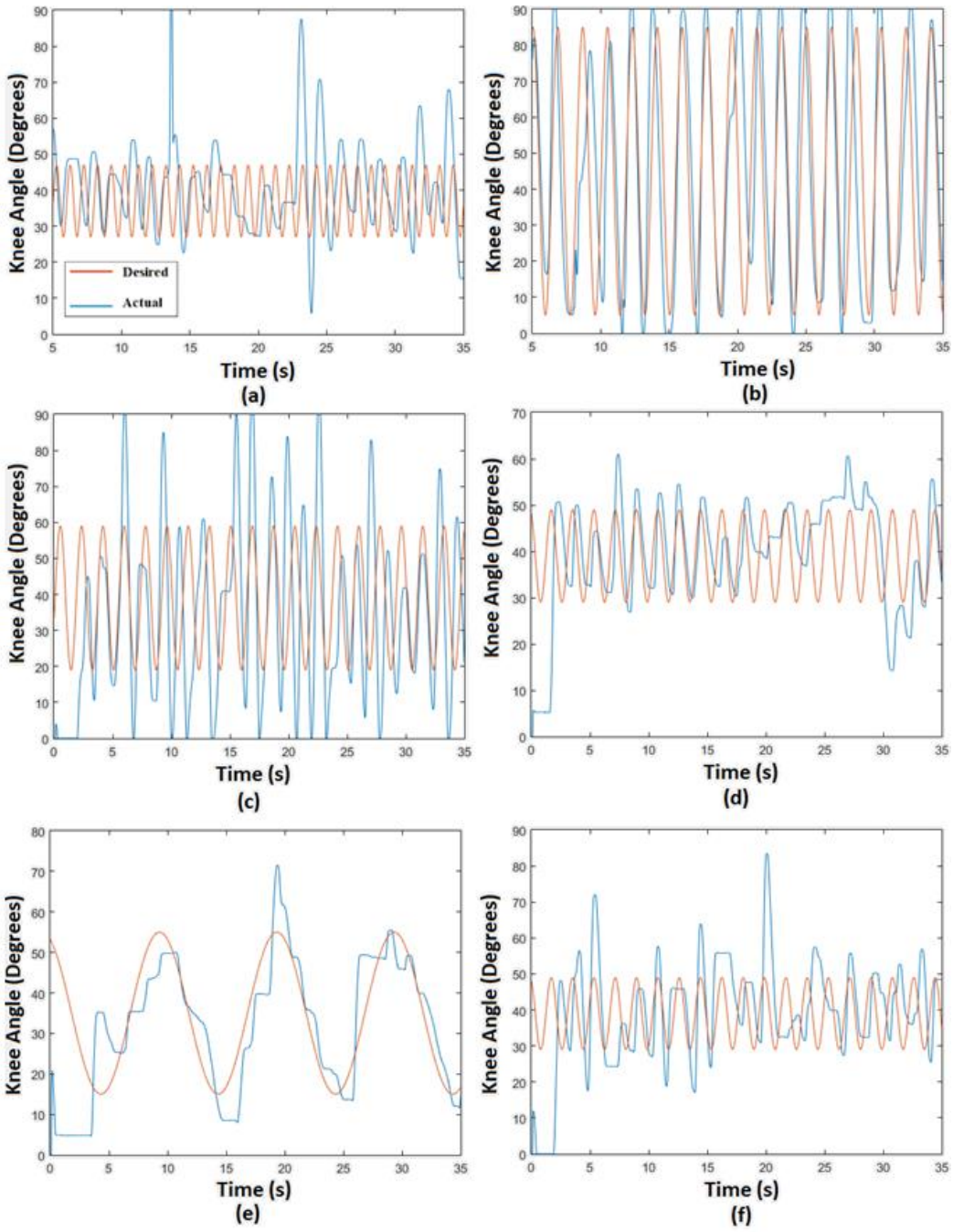

Figure 15: Example task tracking of the powered limb showing (a) no haptic or visual feedback, (b) quasi-static pressure without visual feedback, (c) visual without haptic feedback, (d) vibratory without visual feedback, (e) quasi-static pressure with visual feedback, and (f) vibratory with visual feedback.

It is evident however, as presented in the error plot of Figure 13, that the inclusion of haptic feedback significantly improved performances, tightening up the observed variances across all tests. The testing scenario that yielded the best performance, outside

of the control, was that of quasi-static pressure feedback with concurrent visual feedback. Motion tracking tasks for this configuration are presented in Figure 16 for slow, medium, and fast tracking frequencies.

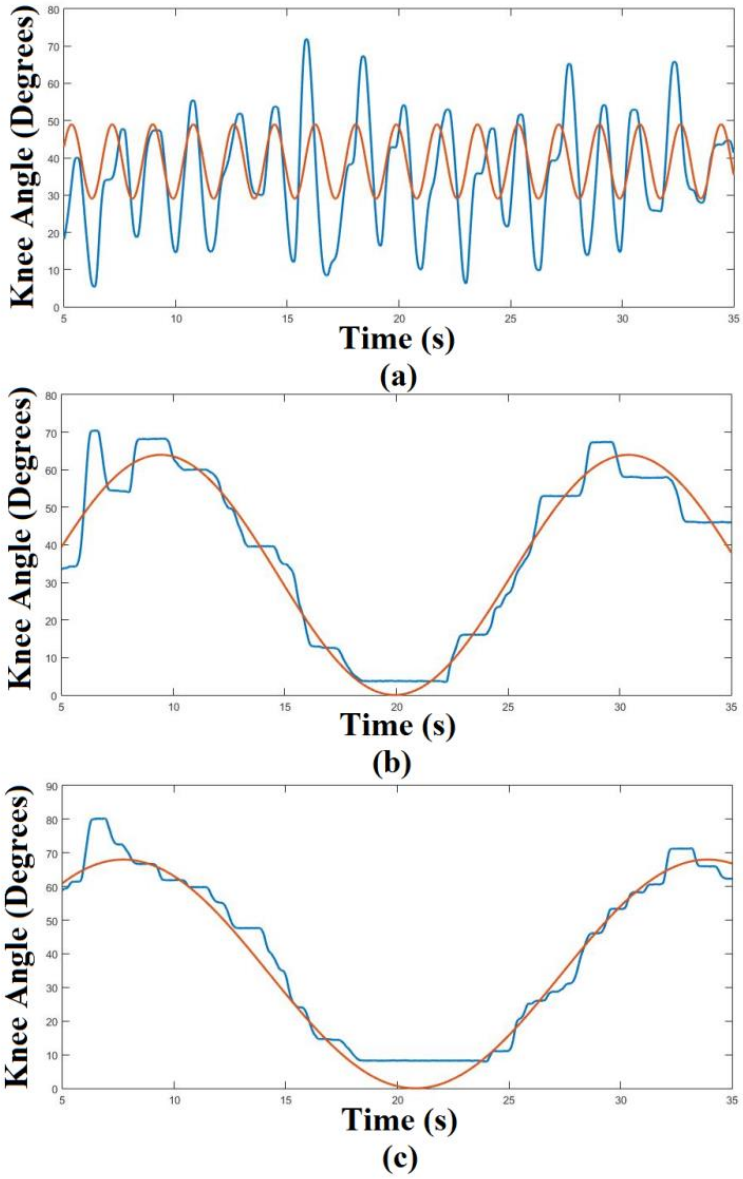

Figure 16: Three individual motion tracking tasks where subjects were provided visual and quasi-static pressure haptic feedback at frequencies of (a) 0.68 Hz, (b), 0.11 Hz, and (c) 0.06 Hz

It was shown, through statistical analysis of the data sets, that the presence of static pressure or vibratory haptic feedback in visually deprived environments allowed for significantly improved performance over attempting motion tracking tasks in an environment deprived of both visual and haptic feedback cues ($p = 0.0001$ and $p = 0.0004$, respectively). Another interesting observation is the significantly higher variances observed in the tests where visual feedback was supplied, except in the visual feedback and quasi-static pressure feedback (Figure 13). Possible reasons for this observation will be conjectured in the discussion. There were no significant performance differences in amplitude tracking amongst any of the tests, as shown in the error-plot of Figure 14. Note how large the variance of the control is compared to everything else. Because of this, there is nothing to conjecture about the incorporation of haptic feedback and the ability to match the desired amplitude of a trajectory with and without visual feedback.

5. Discussion

The inability for the system to successfully convey desired knee angle magnitude content and frequency content simultaneously was largely a limitation of the haptic feedback system used. The haptic feedback arrays only had three tactors and could therefore provide only limited spatial resolution.

Interestingly, when looking at Figures 13 and 14, one can observe that the inclusion of visual feedback yielded markedly larger variance in performance than when visual feedback was removed. This detrimental effect that visual feedback had on the tracking of a rhythmic motion has been well documented as a psychophysical phenomenon, wherein active focus on rhythmic tasks often leads to detrimental over and

under performance by the user, as discussed further in III.C.3 and (Canino, 2017; Canino 2016C).

Results from Canino et al. also suggest that the implementation of corrective haptic feedback could be used to train proper locomotor techniques vis-a-vis forced motion tracking. That is to say, such a haptic feedback apparatus could provide a gait cadence for the user to follow, similar to the error feedback system featured in the motion tracking tasks. Instead of prompting a subject to follow some arbitrarily generated motion trajectory, one could program the system to teach the user to follow a scalable and adaptable gait trajectory. It is hypothesized that this could greatly speed the rehabilitation process for subjects with lower-limb amputation (Canino, 2016C). To further reinforce this hypothesis, McKinney et al. demonstrated that patients with peripheral neuropathy were able to make significant compensatory gait adjustments with the assistance of haptic feedback. These significant rehabilitation improvements were observed with minimal training and resulted in an increase in step speed, better step cadence, step length, and peak joint power (McKinney, 2014).

The experimental results demonstrated the effectiveness of a three-tactor array for improved frequency tracking in prosthetic limb control. However, the limited resolution of the haptic array prevented subjects from being able to attain good position tracking control except for cases where the trajectory amplitudes spanned the full range of motion of the prosthetic knee. To address this limitation, the next chapter details the development of a haptic array with greater spatial resolution and a stimulation architecture for the array that enables enhanced interaction with the user's mechanoreceptive perception.

V. Design and Experimental Evaluation of Final Haptic Feedback System

A. Design Considerations

Heading into development of the final haptic feedback array, there were numerous criteria and concerns that needed to be addressed.The first criteria that was desired for the new array was comfort. Having a comfortable haptic feedback array that was flexible, lightweight, and made of biocompatible material would make its use more conducive to long-term implementation. This is particularly important when considering this device as not only a rehabilitative aid, but also as a daily-use supplementation to prosthetic limb use.

The most obvious desirable criterion was to increase the spatial resolution of the haptic feedback array. By increasing the spatial resolution, it was proposed that there would be a statistically significant increase in not only the complexity of information communicated, but also in the ability to communicate multi-modal feedback. It was suggested that communication be focused on knee angle and knee torque kinematic/kinesthetic information.

One concerning feature of using vibrotactile feedback was its proclivity to induce desensitization phenomenon. Though desensitization was not as severe in the work presented in section IV.C, it was still a concern when considering testing a larger audience. Because of this, vibrotactile haptic feedback had to be implemented in a way that was dissuasive of desensitization, particularly when considering that the haptic feedback array was to be designed with the intention of long-term use.

While it was desired to increase spatial resolution of the haptic feedback array, it was unclear as to whether or not the inclusion of pneumatic haptic feedback was necessary. Prior investigations had demonstrated that both pneumatic haptic feedback and vibrotactile haptic feedback provided significant performance improvements while showing insignificant difference in their performance with respect to one another (Canino, 2016; Canino 2017). Because of the increased burden of implementing pneumatic haptic feedback (requiring regular replacement of CO_2 cartridges while adding a significant increase in array weight), it was desired to create an array that could leverage the simplicity of vibrotactile feedback alone.

The final consideration that greatly influenced the final design of the final haptic feedback array was the phenomenon of neuropathy. Neuropathy is very common in amputees, meaning that tissue proximal to the site of amputation has poorer sensory innervation. This greatly reduces the capacity for an individual to perceive haptic feedback. Because of this, it was important to consider alternative locations for haptic stimulation and to create a final design that was functionally appropriate for the final site of application.

B. Placement: Reasons For and Against Socket Integration

Residual limb neuropathy can pose a significant challenge when trying to provide supplemental sensory feedback at the socket interface (Desmond, 2010). It then became important to understand secondary and even tertiary locations where haptic feedback could be effectively provided, without the use of invasive procedures like targeted reinnervation therapy.

Many would initially conjecture that the socket environment is ideal when considering haptic feedback implementation in a lower limb prosthesis. Upon first observation, the socket environment offered a solid platform in which to mount a haptic feedback apparatus and its proximity to the injury should make it perceptually easier to comprehend any provided haptic feedback. Unfortunately, this was not as ideal as initially conjectured.

While implementation inside of the socket environment offered the most logical solution, its practical implementation was limited. The socket environment and its interfacing with the residual limb is a rather complex scenario. In most common instances, the interior socket environment must be able to maintain a Net Negative Pressure (NNP) in order to keep the residual limb attached to the prosthesis via a suction or suspension sleeve (Beil, 2002). The incorporation of a haptic feedback device would require special crafting of a socket or sleeve that could still maintain this NNP environment while also maintaining constant contact of the haptic feedback apparatus to the subject's limb. There are also considerable forces and pressure changes being experienced inside of the socket environment during regular use. These would also have to be accounted for when not only considering the longevity of a haptic feedback array, but also the effects that changing pressures and forces would have on one's capacity for interpreting haptic cues (Beil, 2002).

Even if these considerations could be properly accounted for, there still remains the fact that neuropathic conditions are common in the tissues proximal to the site of amputation. No matter how the haptic feedback array could be designed, it could not overcome the distinct lack of perceptual awareness that comes with a neuropathic state.

Because of this it was beneficial to evaluate alternative sites for haptic stimulation. It was hypothesized that the best site for implementation was the anterior forearm.

C. Placement: Anterior Forearm as an Alternative Site

The anterior forearm offers unique mechanoreceptive benefits when compared to the thigh tissue proximal to the site of amputation. The forearm possesses five main types of mechanoreceptors: SA I, SA II, hair units, field units, and Pacinian units (Morioka, 2008). The hair units, SA II, and Pacinian units are all sensitive to vibrocatile stimulation (Morioka, 2008). While Pacinian corpuscles are most densely located in the distal hands and feet, their local density decreases as one moves further away from these locations (more proximal). Pacinian corpuscles already have a fairly poor spatial resolution because of their depth in the dermis, but higher innervation density should provide better resolution (Ashmore, 1990). The Pacinian corpuscles can also best be stimulated on the forearm tissue using a frequency of approximately 250 Hz (Morioka, 2008; Verrillo, 1966). It is important to also consider the physiological effects of hair follicle receptors and SA II, which may also play a role in vibrotactile perception, albeit at a lower frequency range of ~ 65 Hz (Ashmore, 1990; Bark, 2010).

The efficacy of vibrocatcile forearm stimulation for substitutional perception has also been demonstrated in literature. In 2016, Shokur et al. investigated the creation of an immersive virtual environment for paraplegics via haptic feedback grids mounted at the forearm. This haptic feedback system was used to impart an artificial perception of the lower limbs and they were able to successfully convey simulated walking on three different textured environments: sand, paved street, and grass (Shokur, 2016).

With these facts considered, it was proposed that the anterior forearm could be perceived better than the proximal thigh tissue as it likely has a higher density of Pacinian corpuscles and thereby a better spatial resolution, while the thigh likely has a lower density and resultant lower spatial resolution (Marioka, 2008). It was then important to experimentally evaluate this proposition, and understand whether or not the forearm could provide an appropriate site for communicating lower limb kinesthetic and kinematic information.

D. Experimental Evaluation of Alternative Placement Sites

It was hypothesized that there existed locations on the body other than the residual limb that could still convey meaningful sensory input when supplied with haptic feedback. As the focus of this work was on transfemoral amputations, locations were chosen ipsilateral to the site of amputation. Locations included the outer thigh (the tissue proximal to the site of amputation) and the ipsilateral anterior forearm. The thigh was chosen because it is the site of the socket interface and the ideal location to implement the haptic feedback device. It also worked to give a baseline to compare the effectiveness of all other locations. The proximity and perception tests then sought to investigate the efficacy of haptic feedback communication of one bodily region's state but applied at a physically different location.

This testing was conducted using a Simulink code that would randomly generate an excitation pattern between two affixed vibrating motors. The distal-most vibrotactor would express desired extension while the proximal most vibrotactor would express desired flexion. The subjects also had Otto Bock 13E202 EMG electrodes affixed to their quadriceps and hamstrings, the desired extension and flexion muscle groups respectively

for prosthetic limb control. During testing, able-bodied subjects without any noted neuropathy were sequentially provided either flexion or extension stimulation at one of the aforementioned locations, upon which time the standing subject would then extend or flex their leg in response. The test included a control, wherein the subject was informed of the precise tactor that would be actuated, but the time at which it actuated was random. This was in an effort to establish baseline responsiveness for each subject.

Testing was also conducted for the thigh and anterior forearm regions while the subject was performing upper limb tasks, specifically a cup-stacking task. During the cup stacking task, the participant was asked to take a stack of 6 cups and build a tower with them while simultaneously performing the test, if they completed the tower before the test was over, they were asked to stack the cups back up and begin again. The subject was also tasked with performing the test with a silicone sheet affixed to their thigh, between the skin and vibrotactors, in an effort to convey a neuropathic state. Each possible test was performed a total of 6 times per subject. For clarification, see Table 2 below.

Table 2: All possible tests for proximity and perception testing.

Location	Test Type
Thigh	Normal
Forearm	Normal
Thigh	Normal + Cup Stacking Task
Forearm	Normal + Cup Stacking Task
Thigh	Normal + Artificial Neuropathy
Thigh	Control

EMG data and vibrotactile stimulation data was recorded through the Simulink program for analysis. Analysis was conducted using one-way ANOVA to explore the efficacy of each location at conveying meaningful sensory information. This will mean looking at both the accuracy of the subject performance (i.e. did they flex when it told them to flex or did they erroneously extend?) and the response time of the subject (i.e. does communication of lower limb information at the forearm yield a delayed response?).

Preliminary data analysis showed that the forearm location without cup-stacking task performs markedly better than the thigh location without cup-stacking task. However, when a cup stacking task was involved, performance between the two locations was comparable. This preliminary data confirmed our hypothesis that the anterior forearm can be an effective location to supplant our sensory feedback. It is also interesting to note that the forearm provided a better feedback experience when the upper limbs are not involved in any motor tasks. This is likely due to the anatomical distribution of Pacinian corpuscles in the human body and the increased spatial focus that our body apportions to upper extremities (Purves, 2001).

E. Development of a High Resolution Haptic Feedback System

The final haptic feedback system was designed for integration on the anterior forearm and with additional tactors to enable greater spatial resolution. The design features a 3x5 grid of vibratory motors, as shown in Figure 17. The design of this grid was further informed by work done by Novich et al., who demonstrated necessary spacing dimensions for independent perception when using vibrating motors (~ 6 cm), and proper usage of spatiotemporal sweeping for enhanced resolution and perception in closer spacing (Novich, 2015).

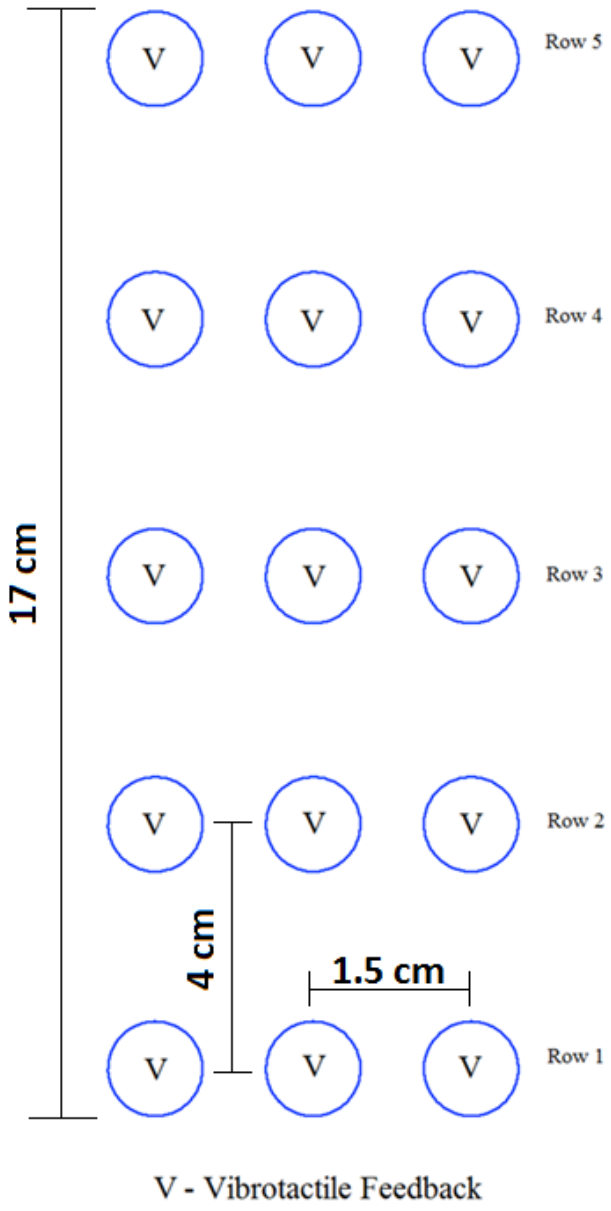

Figure 17: High resolution haptic feedback array vibrotactor arrangement and dimensions.

Arrays were produced using 3D-printing techniques with a material called NinjaFlex™, a printable elastomer, which will allow the array to easily conform to the user's anterior forearm. The array was also shaped in such a way as to allow ulnar-radial rotation (supination/pronation) while keeping the tactors in place (Figure 20). The 3D printed array can be seen in Figures 18, 19, and 20. Note that in Figures 18 and 19, three

additional openings for pneumatic tactors were present, but they were not ultimately used in the final design.

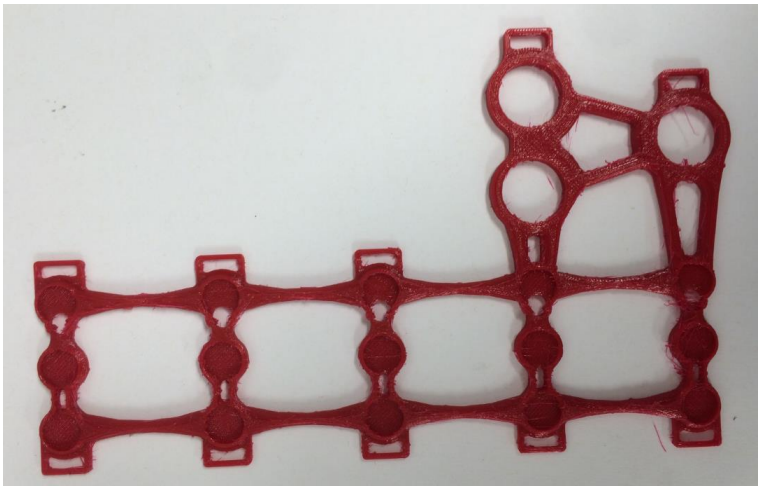

Figure 18: Prototype tactor socket additively manufactured using NinjaFlex™.

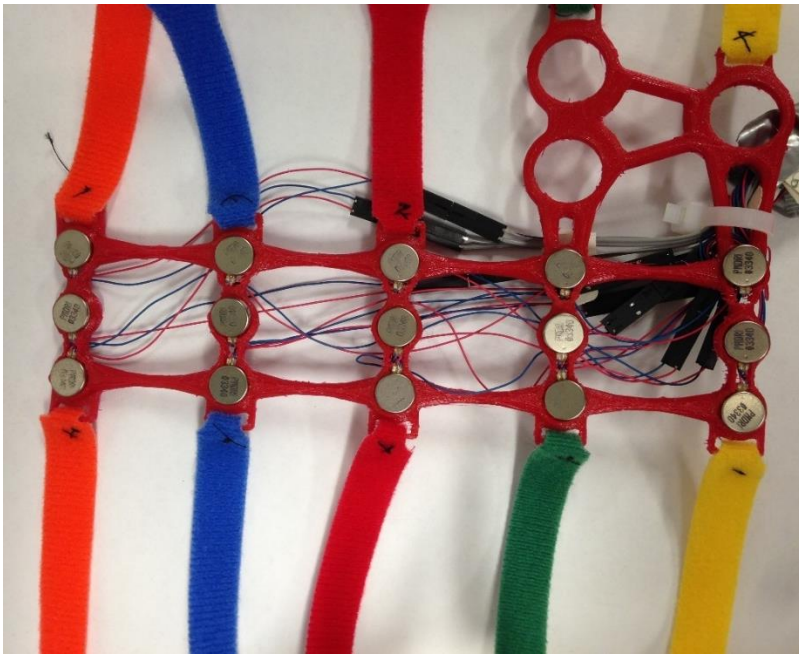

Figure 19: Finished haptic feedback array with installed vibrating motors.

Consistent placement of the haptic feedback device was also important for test repeatability. Initially it was desired to affix the haptic feedback device with a particular

pressure, extrapolated via strain gauge measurements. It was found that keeping the pressure constant lead to variance in haptic perception depending on the individual's subcutaneous fat content. Because of this, the haptic feedback array was instead tightened until every tactor was completely indented into the skin (2mm) and the socket interface was directly in contact with the skin.

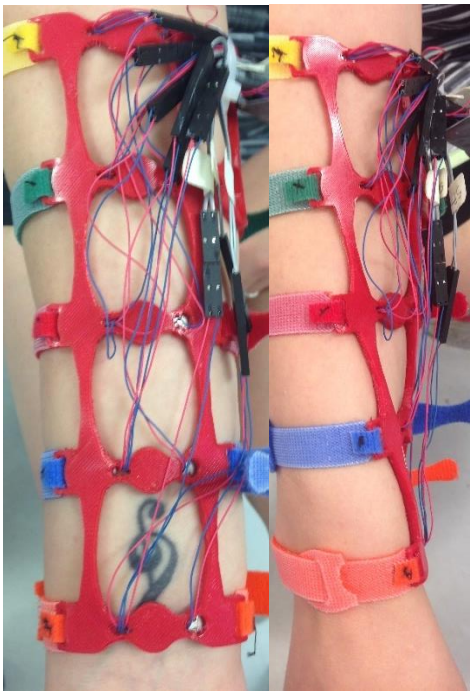

Figure 20: Demonstration of affixed haptic feedback array flexibility in radioulnar deviation and pronation/supination.

A logic circuit was designed and fabricated for use with the haptic feedback device (Figure 21). Because there was a need to actuate 15 different vibrotactors and only 8 digital outputs on the Humusoft MF644 data acquisition board used for experimentation, a logic circuit was required. The circuit featured 15 TIP120 transistors, allowing for the voltage-gated control of 3.0 VDC from a LM4040 series reference voltage diode to each of the 15 individual vibrotactors. The transistors were actuated via AND-gate logic chips (HD74LS08P) which were provided digital input from the

Humusoft MF644 data acquisition board. Digital inputs 1-5 determine which rows are energized and the remaining three inputs determine which motors within the rows are energized.

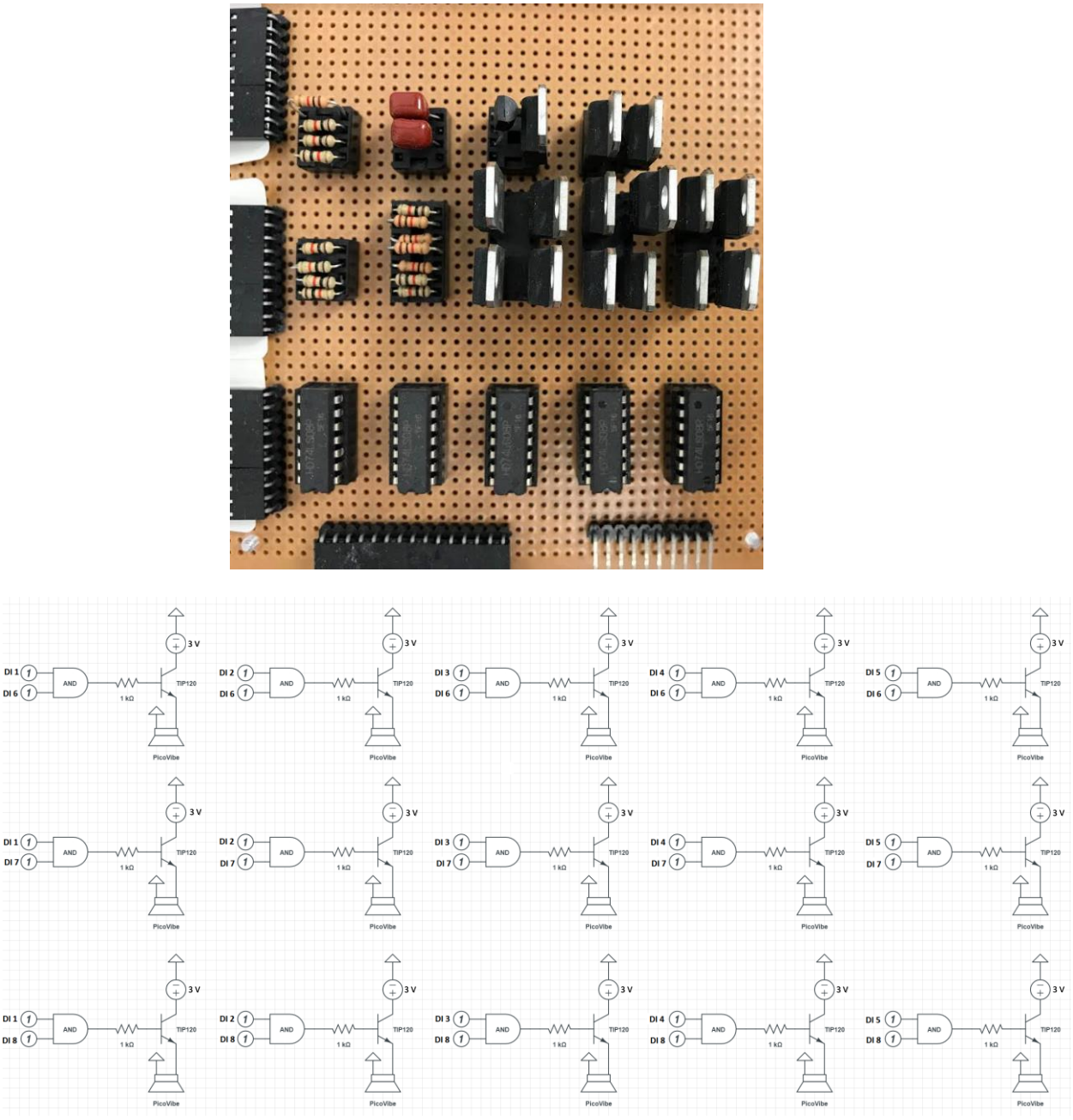

Figure 21: Logic circuit used for actuation of high resolution haptic feedback array with physical circuit (top) and schematic (bottom).

F. Haptic Stimulation Architecture

1. Spatial Architecture

The first of three possible control schemes worked to convey knee angle information through selective activation of tactor rows. In this scheme, rows 1-5 of the tactor array correspond to the knee angles shown in Table 3.

Table 3: Rows and Corresponding Knee Angles

Tactor(s)	Knee Angle-(Degrees)
1***	0^{-}
1	0-10
1&2	10-20
2	20-30
2&3	30-40
3	40-50
3&4	50-60
4	60-70
4&5	70-80
5	80-90
5***	90^{+}

*** denotes rapid pulsatile warning pattern used to indicate hyper-extension and hyper-flexion (row 1 and row 5) respectively.

These ranges were determined by dividing up the possible range of knee angle into 9 knee angle ranges. This field size was chosen based on empirical tuning. The terminal 90 and 0 degrees were expressed by a rhythmic on/off actuation of the 250 Hz stimuli at a frequency of 1 Hz. Should the user attempt to drive the knee beyond its mechanical range of motion, in flexion or extension, a strong pulsatile "warning feedback" was imparted by on/off actuation of the 250 Hz stimuli at 2 Hz. If the knee is left in a state of rest, the stimulation will decrease to a state of rest in an effort to prevent over-stimulation and desensitization. These hyperextension and hyperflexion states added to the 9 knee angle fields, expanding the final spatial resolution into 11 distinct

combinatorial regions. The rows each contain 3 vibrating motors, which can be used to convey magnitude of estimated torque, where 1 active tactor indicates low torque, 2 active tactors indicates moderate torque, and 3 active tactors (the full row stimulated) indicates high torque. Low, medium, and high torque values were nominally tuned to values shown in Table 4.

Table 4: Torque Range for Spatial Architecture

Tactor(s)	Torque Range (N-m)
Low (middle tactor in row)	0 - 20
Medium (2 outer tactors in row)	20 - 45
High (all 3 tactors in row)	45+

2. Torque Architecture

The second possible scheme was based on communicating limb-torque information. In this schema, row 3 functioned as the central row dividing the field into two directions, flexion and extension torque. As torque was applied, the corresponding directional field (rows 3-5 or rows 3-1) had a proportional amount of tactors activated, with the stimulus pattern extending outward from row 3 (see Figure 22). As the torque approached an established limit, all of the tactors in the directional field were actuated and the system began to impart an increasing frequency (cycling on/off actuations per second - 1 Hz, 2 Hz, and 3 Hz) and magnitude (number of tactors cycling on/off in a row – 1 , 2 , and 3 tactors) pulsatile feedback rhythm. This culminated into a strong pulsatile "warning feedback," (all tactors of one field would cycle on/off asymmetrically at

frequencies ranging from 1 to 3 Hz) when the subject drove the limb to the torque limit. This type of error feedback was also presented if the user drove the limb to its mechanical limits (hyper-extension or flexion), but it was distinct from the high-torque warning in that only row 5 or row 1 was actuated. Note that this system did not convey knee-angle state information outside of warnings when the limb had reached its mechanical limits. It was proposed that in rhythmic processes like gait, it may be sufficient (or better) to just provide limb torque information as it is simpler and possibly more intuitive.

Figure 22: Torque-dominant model examples in the extension direction with the top row showing torque within a normal range while the bottom row shows how torque approaching the torque limit will lead to an increase in the number of tactors pulsing (shown by jagged edges around the tactor).

3. Switched Spatial-Torque Architecture

The third possible scheme was a combination of the prior two schemes. The spatial-dominant scheme was used to describe the swing phase of gait (or any motion

wherein ground interactions are not observed) while the torque-dominant scheme was used to convey torque information during the stance phase. The transition between the two schemes was dictated by foot-ground sensor information. When heel strike was initiated, the system transitioned into the torque-dominant scheme. This was intuitive as the limb was essentially anchored by foot-ground interactions, meaning that the user didn't need to worry about the limb's spatial orientation and could instead focus on torque information. Once the foot left the ground (toe-off) the system transitioned back into a spatially-dominant scheme that conveyed knee angle information as shown in Figure 23. It was proposed that this bi-modal scheme would offer the best performance benefits.

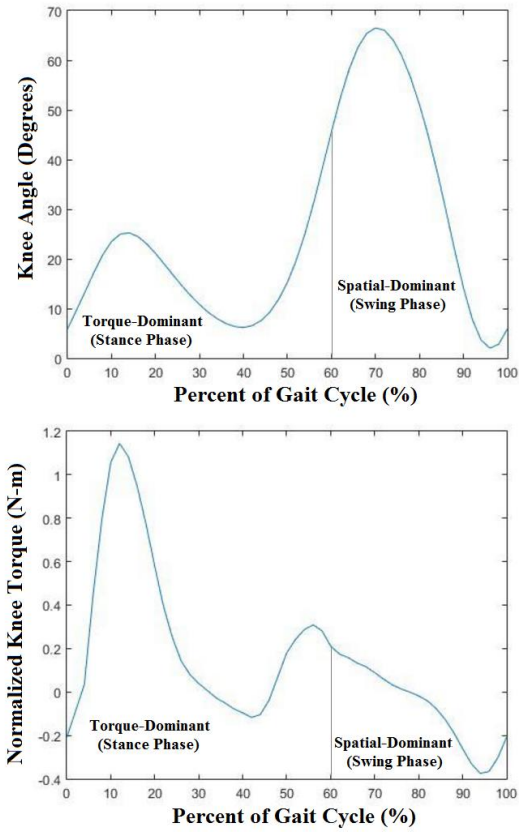

Figure 23: Graph showing combined haptic feedback scheme and transition between torque and spatial dominant schemes throughout the gait cycle.

G. Pilot Study and Elimination of a Control Scheme

Preliminary investigations with the three control schemes demonstrated that the torque-only scheme was difficult to comprehend. Users were tasked with identifying the powered prosthetic limb's position and the kinesthetic/kinematic states that the limb was experiencing. Users were able to understand that the limb was experiencing a torque magnitude about the knee, but they had limited understanding of the limb's position. Even with the inclusion of pneumatic haptic feedback, which could communicate foot contact, users had very poor understanding of knee position and how the limb had moved when only provided torque information. Despite continued redesign and re-testing of the torque-only scheme, it was ultimately dismissed from subsequent testing. From these preliminary investigations, it seems that understanding of limb position is more perceptually important than the limb torque. Torque information is not useless however, as subsequent studies demonstrated that the inclusion of a spatial-torque combined scheme could be important.

H. Haptic Feedback Perceptual Awareness Trials

1. Purpose

The purpose of these trials was to compare the efficacy of the new haptic feedback array to that of the previous haptic array. The specific comparison to be made was the perceptual resolution of knee angle. This was done by having test subjects perform identification tasks, wherein they were asked to identify a knee angle presented via haptic feedback. It was proposed that with the new high resolution haptic feedback apparatus, users should exhibit significant improvement in the accuracy of knee angle

identification from the haptically communicated spatial information. This hypothesis made sense as there are 11 distinct spatial fields for the new array versus the 5 for the original feedback array. The 11 distinct spatial fields used for the high resolution haptic feedback array is as described in Table 3 of V.F.1, while the 5 fields used for the original haptic feedback array are shown in Table 5.

Table 5: The 5 spatial fields for the original haptic feedback array.

Field	Tactor(s)	Knee Angle (Degrees)
1	1	9 ± 9
2	1&2	27 ± 9
3	2	45 ± 9
4	2&3	63 ± 9
5	3	81 ± 9

2. Protocol

This experiment was conducted on 6 able bodied individuals under Clarkson University IRB #14-34. Each subject completed two test sessions, one to evaluate the new haptic feedback array and another to evaluate the old haptic feedback array. Subjects were first informed of the test protocol and provided informed consent documentation for consideration. Consenting subjects donned one of the randomly selected haptic feedback apparatuses (5-field or 11-field), mounted on the anterior side of their dominant forearm. The subject was then presented an initialization sequence, wherein the haptic feedback array would sweep from 0 to 90 degrees over a period of 10 seconds and back from 90 to 0 degrees over another 10 seconds. During this initialization sequence, subjects were also shown a visual display of the changing knee angle value. Subjects were subsequently

provided a randomly generated knee angle via haptic feedback alone (selected from 0 to 90 degrees in possible decimations of 1 degree). They would be asked to identify this knee angle to the best of their ability. This process was repeated 12 times during a single test session. This testing session would then be repeated on a subsequent day using the haptic feedback array that was not used on the prior day of testing.

Note that when asked to identify knee angle with the original 5-field haptic feedback array, subjects were not asked to prescribe a specific knee angle. They were instead tasked with identifying the perceived knee angle range, labeled as their respective fields 1-5, as presented in Table 5. For example, if the program randomly generated the knee angle 23 degrees, the subject would have to correctly identify "field 2," which corresponds to tactors 1 and 2 being actuated simultaneously. This was done in an effort to minimize error that would come from subjects arbitrarily ascribing a specific knee angle, which is not possible with the resolution of the original 5-field haptic feedback array.

For the high resolution 11-field haptic feedback array, subjects were informed of the distinct spatial fields, but were asked to provide specific perceived knee angles, rather than a range. This was done for two reasons, the first being that in pilot testing it was observed that it was nearly impossible for users to identify the specific tactors being actuated on the high resolution 11-field array – the sensation was perceived as a linear continuum rather than a discrete set of fields. The second reason was to make the testing more statistically strenuous on the 11-field array. That is to say, allowing for subjects to provide specific perceived knee angles should increase the error margin of the new system. It is also important to note that when actuating the 11-field haptic feedback

array, all three tactors of a given row were activated. This was done because it was unclear at the time whether or not the three tactors being actuated at the same time would increase or diminish haptic perception. Based on works by Morioka and Verrillo, it was suggested that there would be an increase in haptic perception, correlated to the increase in effective vibratory magnitude (no change in frequency) (Morioka, 2008; Verrillo, 1966).

3. Analysis

Analysis was conducted on the Root-Mean Squared (RMS) deviation data of the desired knee angle versus the identified knee angle. When analyzing the RMS deviation for the 5-field haptic feedback array, the median of the identified range was chosen for the effective identified knee angle. This data was then compared using ANOVA via SPSS.

4. Results

Figure 24 shows the plot of means of the RMS error data for the 5-field apparatus versus the 11-field apparatus.

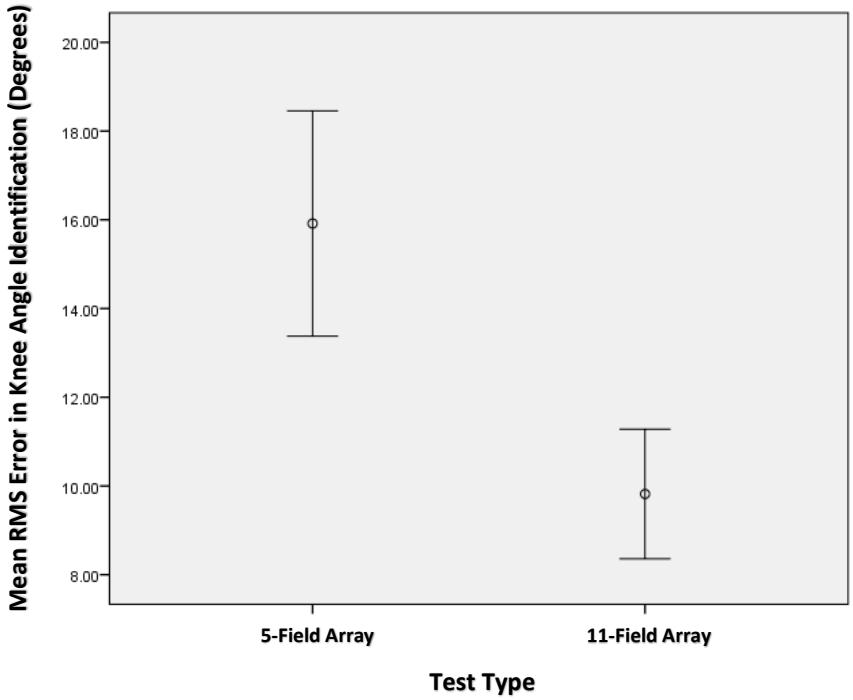

Figure 24: RMS error data for knee angle identification utilizing the 5-field apparatus or the 11-field apparatus.

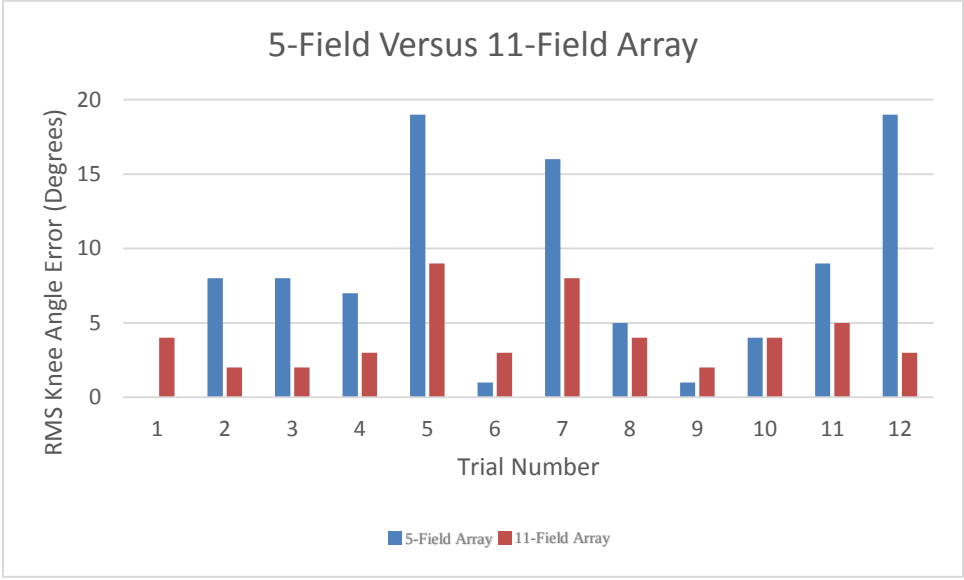

Figure 25: Bar chart showing RMS error for 5-field array versus 11-field array.

The mean RMS error for the 5-field apparatus was approximately 16 degrees while the error for the 11-field apparatus was approximately 9 degrees. The 11-field haptic

feedback apparatus offered a statistically significant performance improvement over the 5-field apparatus, with a p-value of 0.0001. A performance accuracy comparison can be seen in Figure 25, wherein one subject's performance with the 5-field array is shown versus the 11-field array.

5. Discussion

While this testing and its results may seem like a forgone conclusion, it was important to better understand if the increased spatial resolution provided by the new haptic feedback array would offer any discernible difference in perception of spatial information. This is a particularly important question when considering the relatively vague understanding of mechanoreceptor innervation density on the anterior forearm. Based on the results from the statistical analysis, it is clear that the new system provides a significant improvement with respect to spatial perception, nearly halving the magnitude of error when compared to the original haptic feedback array. Qualitative observations also demonstrated that there existed a seeming perceptual continuum of haptic information rather than discernible haptic fields with the new haptic feedback array. It is hypothesized that this relates to the anatomical properties of mechanoreception, wherein Pacinian corpuscles and their respective innervation densities offer a perceptual spatial resolution limit. This could also be due to the aforementioned suggestion that having three tactors simultaneously actuated provides a higher effective vibratory magnitude. This increase in stimulation magnitude, combined with the innervation density, could mean that the new system has effectively reached a perceptual saturation limit of the anterior forearm (Morioka, 2008; Verrillo, 1966).

VI. Gait Motion Trajectory Tracking & Replication Trials

A. Purpose

Now that the communicative benefits of using the new high resolution haptic feedback array were better understood, it was important to test the system's capacity to communicate complex trajectories, such as those required for locomotor function. This was done by first creating a real-time method of evaluating human gait, utilizing the knee goniometer detailed in II.E. The real-time evaluation methodology was also used to create a library of knee trajectories at various speeds. Able-bodied test subjects were then tasked with the real-time tracking or replication of these locomotor trajectories. During motion tracking, subjects were tasked with following a gait pattern consisting of a stride-normalized knee trajectory repeated at a specific cadence. The trajectory was presented to subjects via the haptic array, and they choose the speed of treadmill walking to match the presented gait pattern. During motion replication tasks, subjects were temporarily presented a gait trajectory via the haptic array and subsequently tasked with replicating that motion from memory while only being provided real-time kinematic and kinesthetic information about their knee via haptic feedback. Performing these tests on able-bodied individuals allowed for a more statistically isolated evaluation of the haptic feedback apparatus and control schemas while avoiding any confounding factors that may have come with the use of amputee test subjects.

B. Modified Knee Goniometer

The knee goniometer, shown in Figure 26, was constructed to allow for the analysis of limb motion performed by able-bodied test subjects. It was composed of a modified universal-fit Townsend Stability Boot (TSB), which is a Controlled Ankle

Movement (CAM) walker boot that possessed an inflatable insert to accommodate a variety of limb shapes. The CAM walker boot was chosen as it best mimiced the ankle stiffness of many transfemoral prostheses, essentially eliminating effects of sound ankle compliance and power generation. The boot is affixed to an adjustable scaffold that contained a rotary potentiometer and a formed attachment plate that was affixed to the proximal thigh via Velcro straps. The goniometer was equipped with the same EMG electrodes as are used with the transfemoral powered prosthesis (Otto Bock 13E202), and three pressure sensors on the bottom of the boot. The three pressure sensors measured foot-ground interactions at the heel and ball of the foot. A circuit containing the pressure sensing electronics and input/output terminals was affixed to the distal portion of the boot.

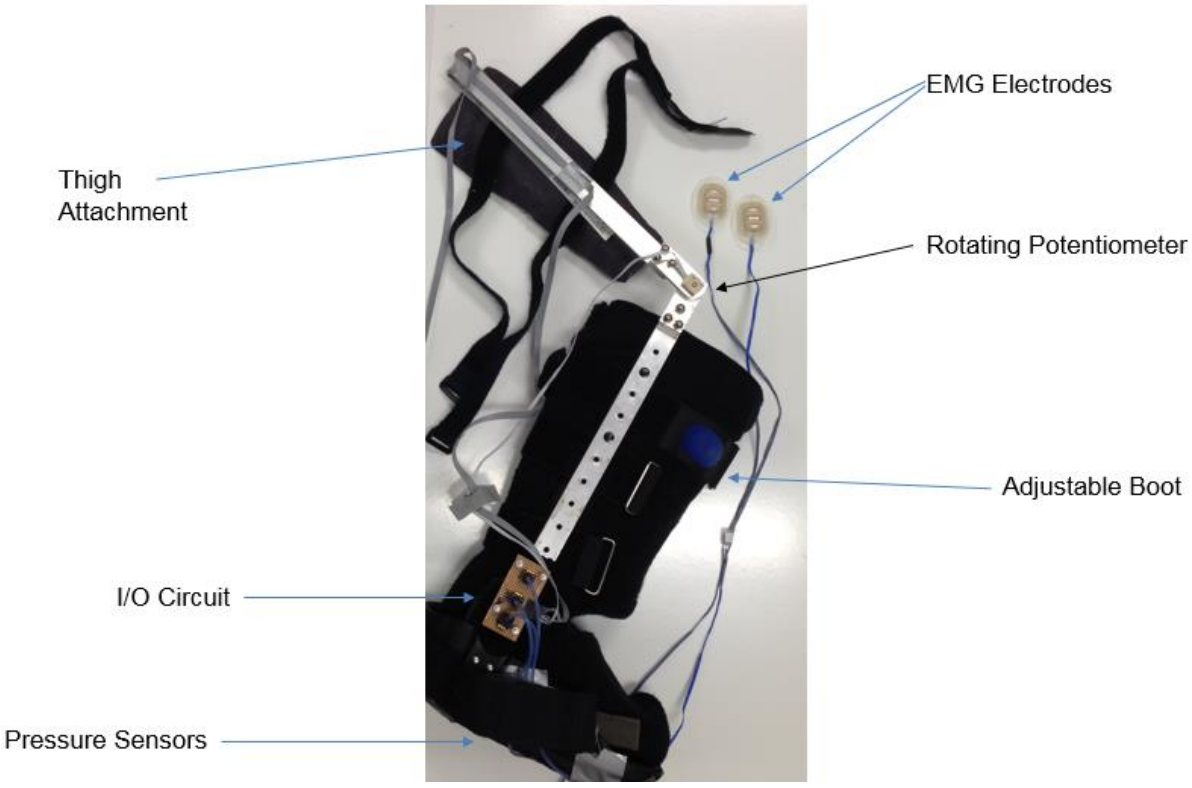

Figure 26: Modified knee goniometer apparatus.

Repeatable placement of the knee goniometer was very important for data consistency and repeatability of tests. In order to obtain this repeatable performance, a goniometer placement protocol was followed for all tests involving the goniometer. The determination of the Center of Rotation (CoR) for the knee was important for aligning the goniometer pivot point. The CoR was determined using anthropometric data and procedure as outlined by Gardner et al. (Gardner, 1969). An example of this CoR mapping is demonstrated in Figure 27.

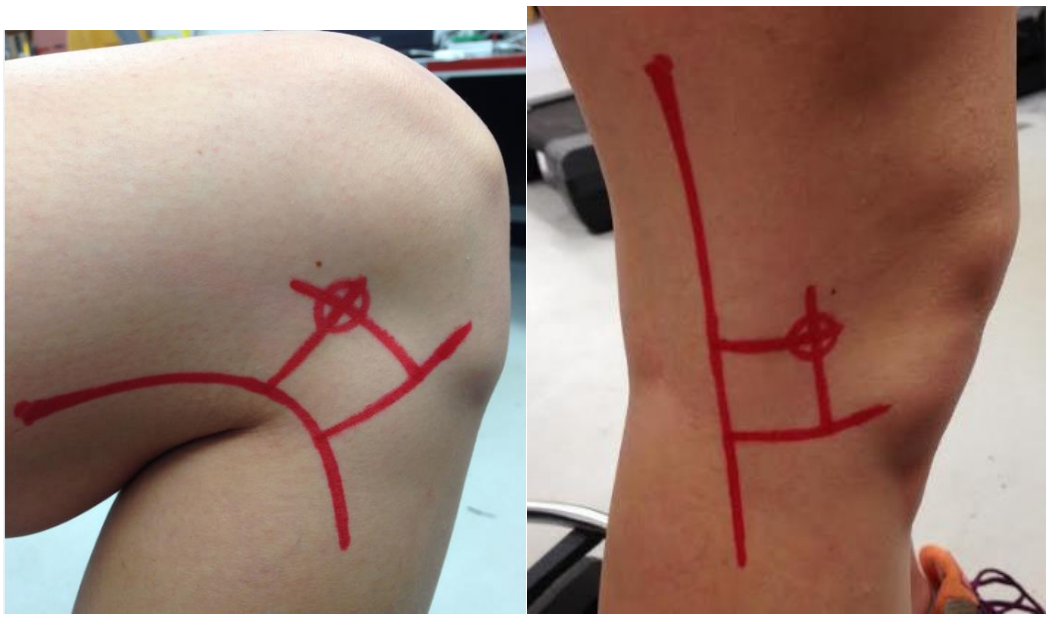

Figure 27: Center of rotation mapped on subject's knee prior to goniometer alignment.

Once this CoR was determined, a small pylon (plastic cylinder) was utilized to assist in visual confirmation of alignment between the knee goniometer pivot point and the CoR. Alignment was adjusted by sliding the scaffolding-boot interface up and down and then tightening locking screws once alignment was achieved. It should be noted that the locking screws were checked and re-tightened during every rest period of testing to ensure that there is no loosening or movement of the scaffolding during trials. Once the

knee CoR was properly aligned with the goniometer pivot, the proximal portion of the goniometer was affixed to the thigh via Velcro straps. The final affixed apparatus is shown in Figure 28.

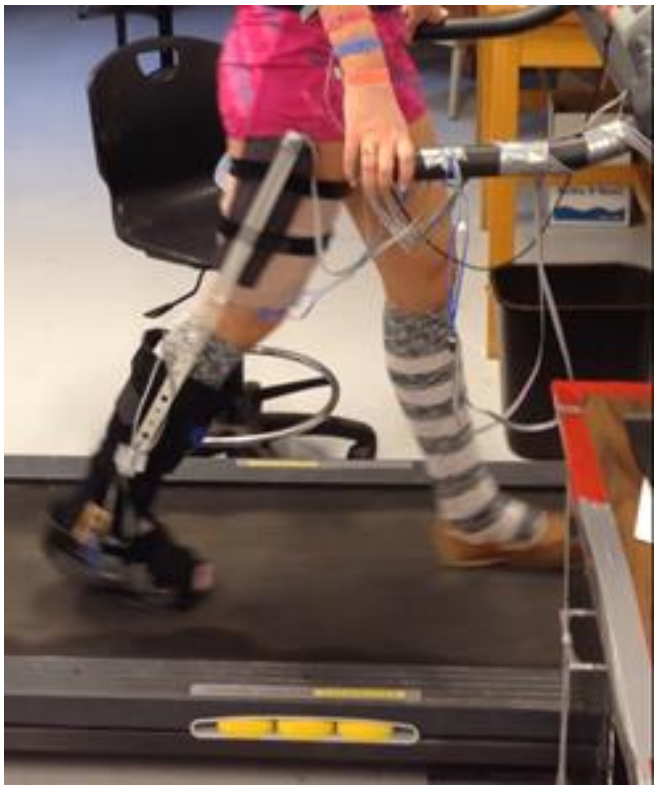

Figure 28: Subject wearing goniometer during stride and cadence testing.

C. Knee Torque Model

It was important to estimate the torque being exerted by the able-bodied knee for post-test analytics and for real-time control of the haptic feedback device. A model was developed that incorporated both the EMG measurements from quadriceps/hamstring muscles and potentiometer data from the knee goniometer to estimate instantaneous knee torque. Because subsequent testing would ultimately utilize the lab's prototype EMG-controlled transfemoral prosthesis, it was also desired to have torque trajectories that

would be demonstrably comparable to the prosthetic system. With this in mind, prior works describing the modeling and control of a powered-knee prosthesis were used as a basis for the able-bodied knee-torque model (Dawley, 2013). A Principal Component Analysis (PCA) was performed on initialization data as described in II.E yielding the same equations (I - II) but with nominally tuned values K_{max}, B, and ω_{max}, describing corresponding stiffness, viscous damping, and maximum angular velocity for the able-bodied knee. These values were determined by starting with anthropometry data and then empirically tuning the parameters until the appropriate normalized torque morphologies were observed (Valle, 2006).

Evaluation of the torque profiles produced by the goniometer and EMG system showed results that were in agreement with other works that have explicitly calculated the knee torque during human gait (McGibbon, 2012). Figure 29 below shows an example gait cycle and corresponding torque profile. Note that the torque profile going from terminal stance into swing was not exactly isomorphic to that of normal human gait demonstrated by McGibbon et al (McGibbon, 2012). This was due in part to fixation of the ankle by the goniometer's boot, making the trajectory more akin to that of the transfemoral prosthesis.

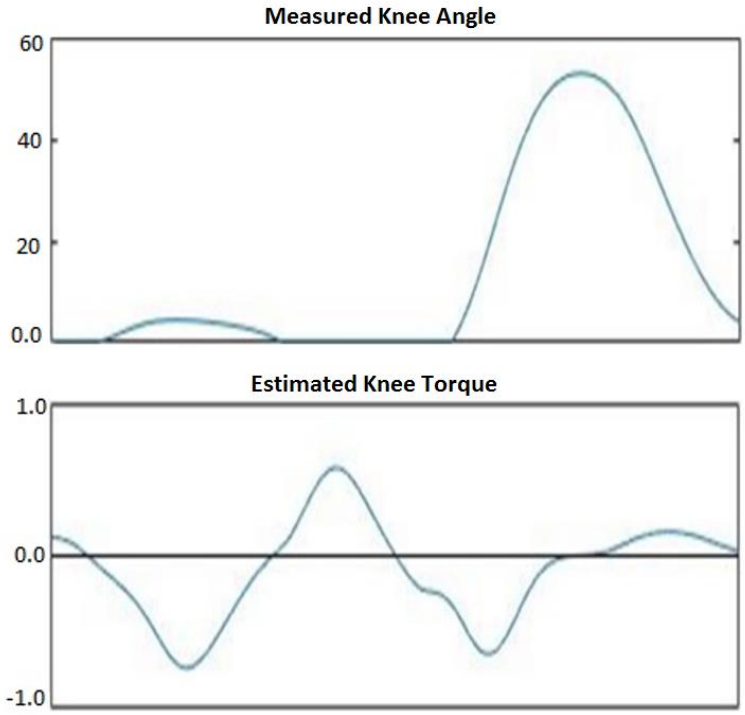

Figure 29: Plot of knee angle and knee torque (where positive torque and knee angle implies flexion) across one full gait cycle.

D. Gait Trajectory Loops

For the motion tracking tasks to be investigated, gait trajectories were created. This was done by having volunteers don the knee goniometer system, complete the calibration routine detailed in II.E, and then walk on a treadmill at speeds ranging from 1.0 mph to 3.0 mph in 0.1 increments, for a total of 21 recorded gait trajectories. Each raw gait trajectory was then ensemble averaged and the average gait cycle was looped (repeated) for a total of 35 seconds. This was done for 7 participants with 21 gait recordings each, ultimately creating a gait-loop repository of 147 motion trajectories that were used for testing. The rationale behind having 7 different participants generating gait loops was to investigate if any significant impact could come from leg-length

discrepancies between the individual who generated the desired gait trajectory and the individual attempting to replicate the trajectory. It was found during post-processing however, that there was no significant variance amongst the final gait trajectories, both in the knee angle and the normalized knee torque values. An example gait loop can be seen in Figure 30.

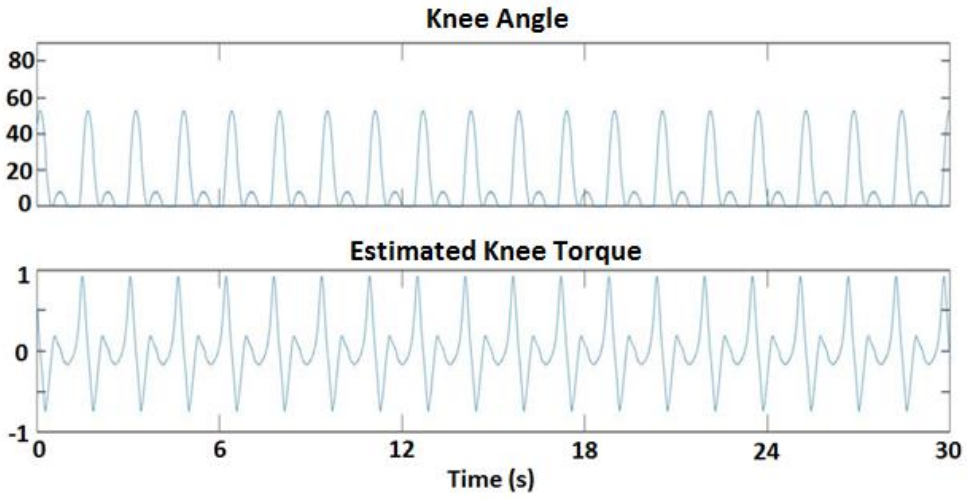

Figure 30: Example gait loop that would be provided to subjects for tracking or replication.

E. Protocol: Motion Tracking Tasks

The first thing that was done before each test session with a new participant was to inform them of the approved IRB protocol for the test and obtain their written consent to participate. After obtaining consent to participate, each subject had the goniometer and EMG electrodes affixed as described in II.D and the haptic feedback array affixed to their forearm as described in V.E. The subject was asked to stand on the treadmill, where testing would occur, and have the appropriate treadmill safety key attached to their

person. The subject would then be prompted to go through the initialization and calibration protocol as discussed in II.E for establishing model parameters.

Before each session of testing, a randomized sequence of motion tracking tasks were selected for that given day's haptic control pattern (either spatial-dominant or combined model). This sequence of tasks included 6 tasks that incorporated haptic feedback and 6 control tests for a total of 12 tasks for the subject per test day. These 12 tasks were repeated across 2 days, one for each communication method. Table 6 shows these testing protocols for the trajectory following tasks.

Control testing occurred randomly during the testing protocol. During the control tests, the subject would be asked to identify the speed at which they were walking. They first walked at three presented speeds: 1.0mph, 2.0mph, and 3.0mph. The subject was then asked to dismount the treadmill and it was set to a randomly prescribed speed between 1.0 and 3.0 mph in 0.1 mph increments. The subject was then allowed back on the treadmill and asked to identify, to their best ability, the speed at which they perceived the treadmill to be moving, without any haptic feedback provided. This control task was chosen to quantitatively evaluate a baseline ability to guess gait speed. If the haptic-integrated testing proved insignificantly different from this control test, then the haptic feedback system would not have provided any measurable benefit. In other words, if the haptic feedback system testing was not significantly more accurate than the control testing, then the subject would be better off just estimating their rate of motion. It was hypothesized that use of haptic feedback would enable the subject to perform significantly better than the control test. Note that during the control tests, subjects were unable to see the display on the treadmill that would normally show the speed as it was

covered with a piece of duct tape. The noise prompts on the treadmill were also disabled so the subject could not count the number of ticks (0.1 mph increments) required to reach the prescribed speed.

For the first test day, one of the two haptic feedback communication methods were randomly chosen, either the spatial-dominant or combined scheme. If one scheme had been chosen for the prior test day, then the other was used on the subsequent testing day. For the haptic feedback tests, the stationary test subject was provided a 1.0, 2.0, and 3.0 mph gait loop via the haptic feedback interface. The subject was then provided a randomly selected gait trajectory via haptic stimulation. The subject was asked to follow the continually playing haptic guidance trajectory by adjusting the treadmill to the perceived speed. Once the subject felt that they were walking at the speed being conveyed by the haptic feedback array, goniometer data was recorded for 35 seconds.

Table 6: Testing matrix for motion tracking tasks.

Test Day	1	2
Communication Method	Randomized Spatial or Combined Haptic Guidance	Method Not Used on Day 1
Tests (Conducted in Random Order)	6 Randomized Control Tests 6 Randomized Tracking Tests	6 Randomized Control Tests 6 Randomized Tracking Tests

F. Protocol: Motion Replication Tasks

For the motion replication tasks, the consent and initialization procedures were conducted as described in VI.E.

Before each session of testing, a randomized sequence of motion tracking tasks were selected for that given day's haptic control pattern (either spatial-dominant or

combined model). This sequence of tasks included 6 tasks that incorporated haptic feedback and 6 control tests for a total of 12 tasks for the subject per test day. These 12 tasks were repeated across 2 days, one for each communication method. Table 7 shows these testing protocols for the replication tasks.

For control tests in motion replication, the subject was instructed onto a treadmill moving at a randomized speed, again between 1.0 and 3.0 mph in 0.1 mph increments. The subject was given 30 seconds to walk at this speed and then asked to dismount the treadmill. The subject was then asked to get back on the treadmill and manually adjust its speed from 0.0 mph until they thought that they were moving at the same speed that had been previously presented. This control test was intended to provide a quantitative basis for normal proprioceptive capacity. If the haptic feedback method did not perform significantly worse than this test, then the haptic feedback system was providing information comparable to that of an able-bodied capacity to replicate previously experienced motion. It was hypothesized that the haptic feedback array would provide performance comparable to that of the control test. Note that during the control tests, subjects were unable to see the display on the treadmill that would normally show the speed as it was covered with a piece of duct tape. The noise prompts on the treadmill were also disabled so the subject could not count the number of ticks (0.1 mph increments) required to reach the prescribed speed.

For the first test day, one of the two haptic feedback methods was randomly chosen, either spatial-dominant or the combined scheme. If one scheme had been chosen for the prior test day, then the other was used on the next testing day. For tests with haptic feedback, the test subject was asked to walk at 1.0, 2.0, and 3.0 mph while being

provided real-time haptic feedback of their real-time limb state according to the communication method prescribed. The subject was then provided with a randomly selected gait trajectory that was haptically communicated to them for 30 seconds while stationary. The desired gait trajectory loop would then be taken away from the test subject and they would be asked to replicate the motion while being provided the real-time haptic feedback information about their limb. Once the subject felt that had been haptically communicated, the data was recorded for 35 seconds.

Table 7: Testing matrix for motion replication tasks.

Test Day	1	2
Communication Method	Randomized Spatial or Combined Haptic Feedback	Method Not Used on Day 1
Tests (Conducted in random order)	6 Randomized Control Tests 6 Randomized Replication Tests	6 Randomized Control Tests 6 Randomized Replication Tests

G. Analysis

Analysis was conducted by comparing the Fast Fourier Transform (FFT) of the recorded trajectory to that of the desired trajectory. Essentially this work sought to investigate the frequency content of the generated trajectory versus that of the desired gait trajectory. The coherence of the data was also analyzed, that is to say the commonality in gait morphology was analyzed. This was done using Magnitude-Squared Coherence (MSC), shown by equation X (Kay, 1988; Rabiner, 1975; Welch, 1967):

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \quad \text{(X)}$$

where MSC uses Welch's averaged modified periodogram method to estimate coherence between two signals with $P_{xx}(f)$ and $P_{yy}(f)$ being power spectral densities and $P_{xy}(f)$ being

the cross-power spectral density. After being evaluated, the data was then compared using one-way ANOVA, using IBM SPSS to conduct the analysis. Note that all data analytics are presented in XI.A.3.

H. Results: Motion Tracking Gait Frequency

Analysis from the motion tracking task showed that both the spatial and combined haptic feedback methodologies produced significant improvement over the control in the identification and tracking of a prescribed gait trajectory, $p = 0.006$ and $p = 0.002$ respectively. The mean of this data and its variance can be seen in Figure 31.

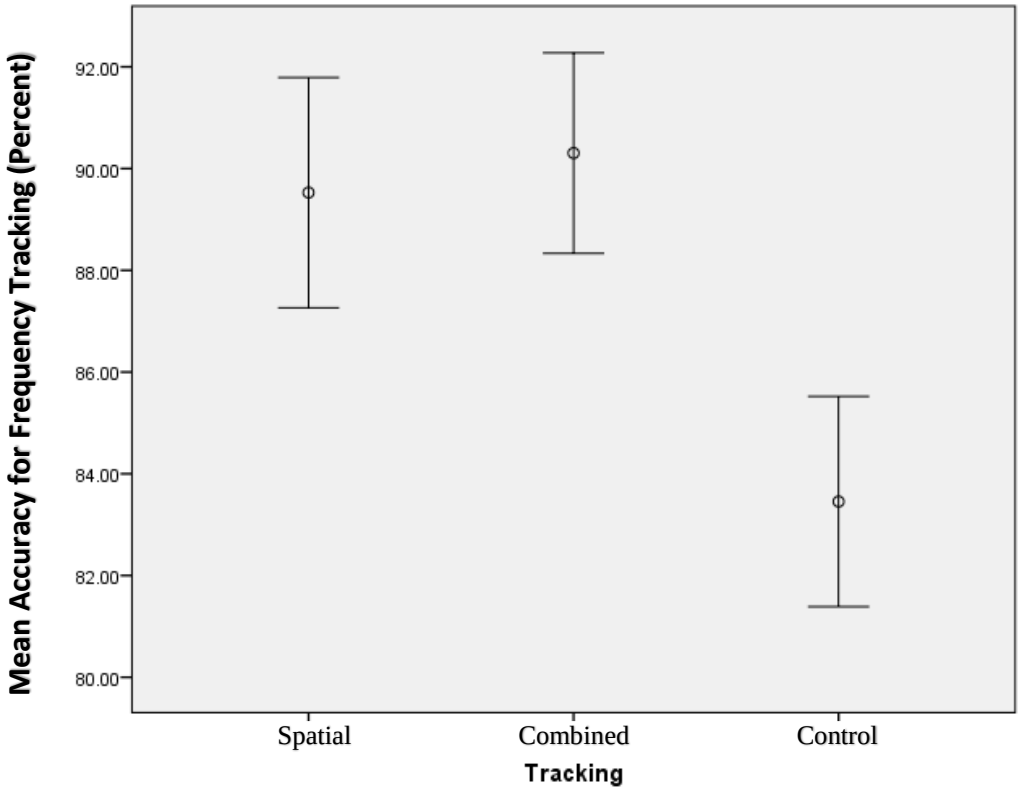

Figure 31: Mean data with error bars for motion tracking task frequency accuracy.

It can be seen in this data that the average performance accuracy for both the haptic methodologies was around 90%. It should also be noted how similarly both of

these methodologies – combined and spatial – performed. There was no significant difference observed between these two systems from the data, p = 0.946.

I. Results: Motion Replication Gait Frequency

Analysis from the motion replication task showed, again, that both the spatial and combined haptic feedback methodologies produced significant improvement over the control in the replication of a prescribed gait, p = 0.001 and p = 0.001 respectively. The mean of this data and its variance can be seen in Figure 32.

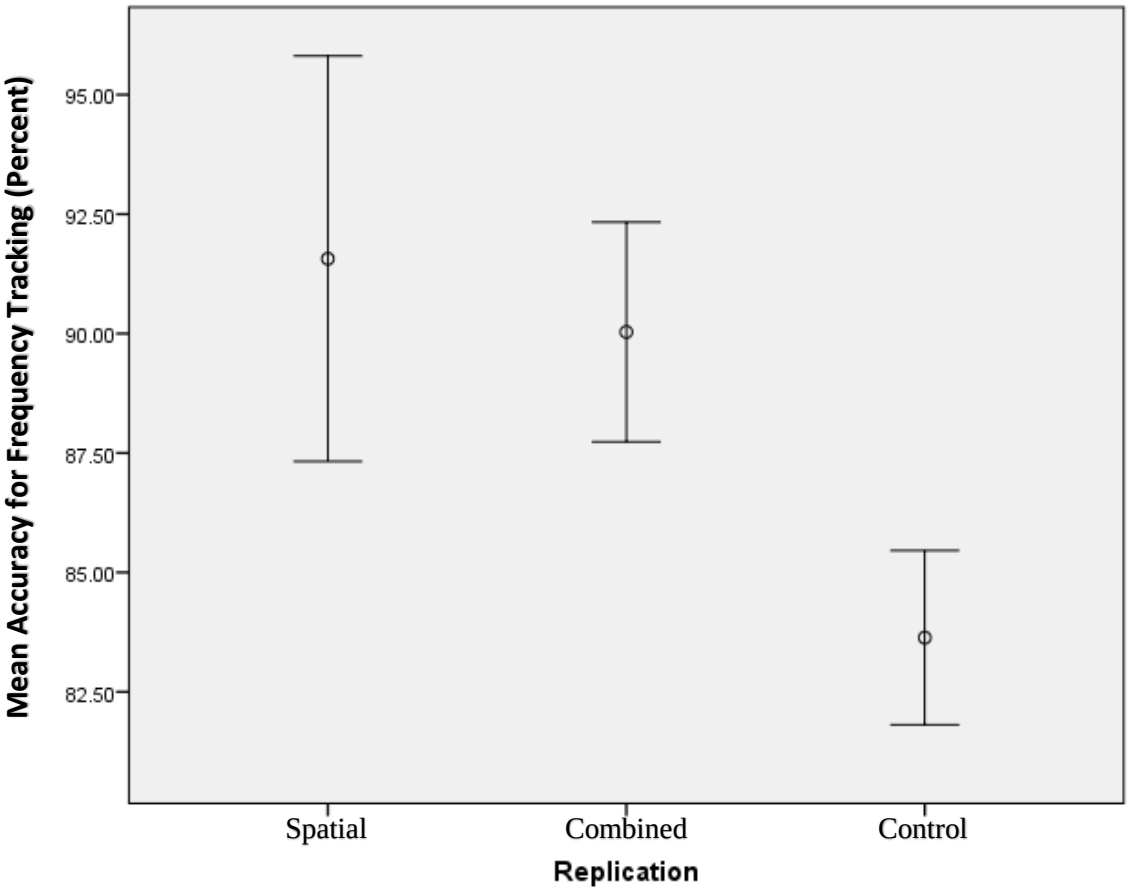

Figure 32: Mean data with error bars for motion replication task frequency accuracy.

Again, one can observe that the accuracy of these motion replication tasks was high, around 90%. As with the motion tracking tasks, the motion replication tasks did not demonstrate any significant difference between communication methodologies, $p = 0.850$.

J. Results: Motion Tracking & Replication Coherence

When looking at the coherence data (Figure 33), that is how well the test subjects were able to follow the communicated trajectory's waveform morphology (locations of characteristic peaks and troughs, period of stride), it is easy to see that there is no significant difference between the test type and communication method.

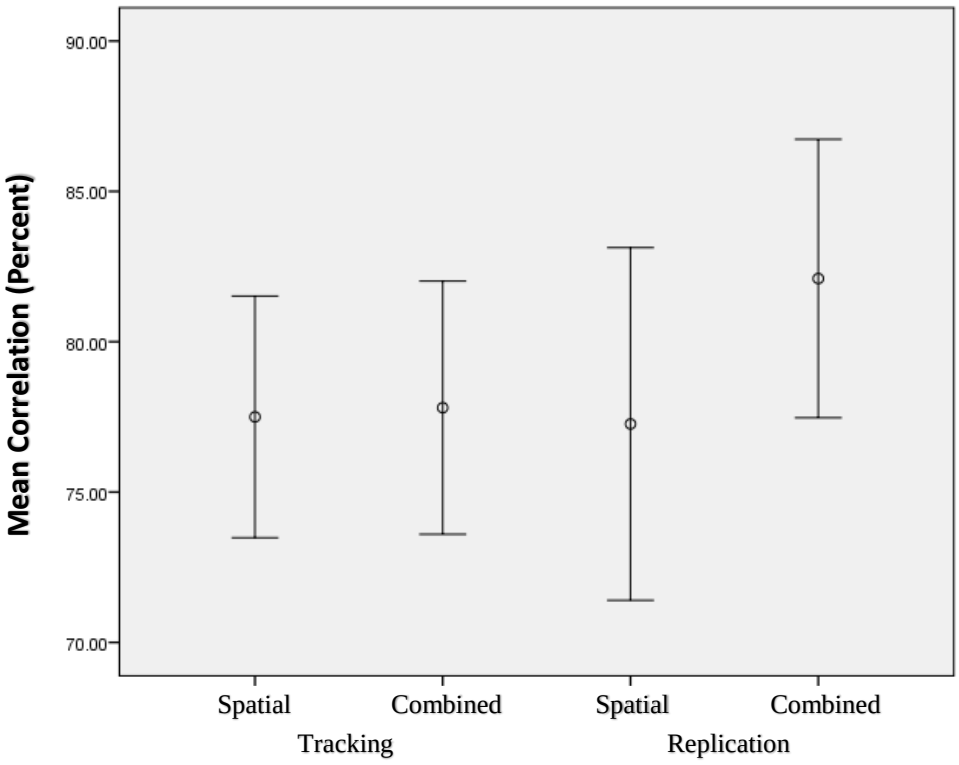

Figure 33: Plot of mean data and error bars for correlation across all tracking tasks.

Though one could conjecture that the replication test with a combined haptic communication method seems to have performed better than its peers (higher average accuracy and smaller standard deviation), the differences are not statistically significant. Some test subjects performed notably better at matching the exact knee angles obtained during gait while others did not, with an overall average correlation of around 78%.

K. Discussion

It is interesting to note how the two tests conducted in the presence of haptic stimulation demonstrated significant improvement over their respective control tests. But it is important to discuss what this means and the impact this will have on future considerations and work. In the tracking task, the purpose of the control test was to demonstrate the innate ability for the body to approximately identify rate of movement. This rate of motion identification is something that someone with a transfemoral prosthesis could do, even without haptic feedback. And the performance was reasonably good, with subjects able to identify their speed with an accuracy of approximately 83%. The subject could generally distinguish the rate at which they were moving with a variance of approximately ± 0.4 mph. When the subjects were provided with continuous haptic prompting, they were able to accomplish this task with a combined accuracy, between both communication methods, of around 90% with a variance of approximately 0.2 mph. This was just as hypothesized; the haptic feedback system yielded significantly improved results. This makes sense because instead of having the test subject guess a value from some seemingly nebulous scale, they were able to use a continuous rhythmic stimulation with which to match their rate of locomotion. An example of this motion tracking task can be seen in Figures 34 and 35. Note how well the subject is able to

follow not only the spatial information being communicated, but in doing so they are also producing a very similar torque profile.

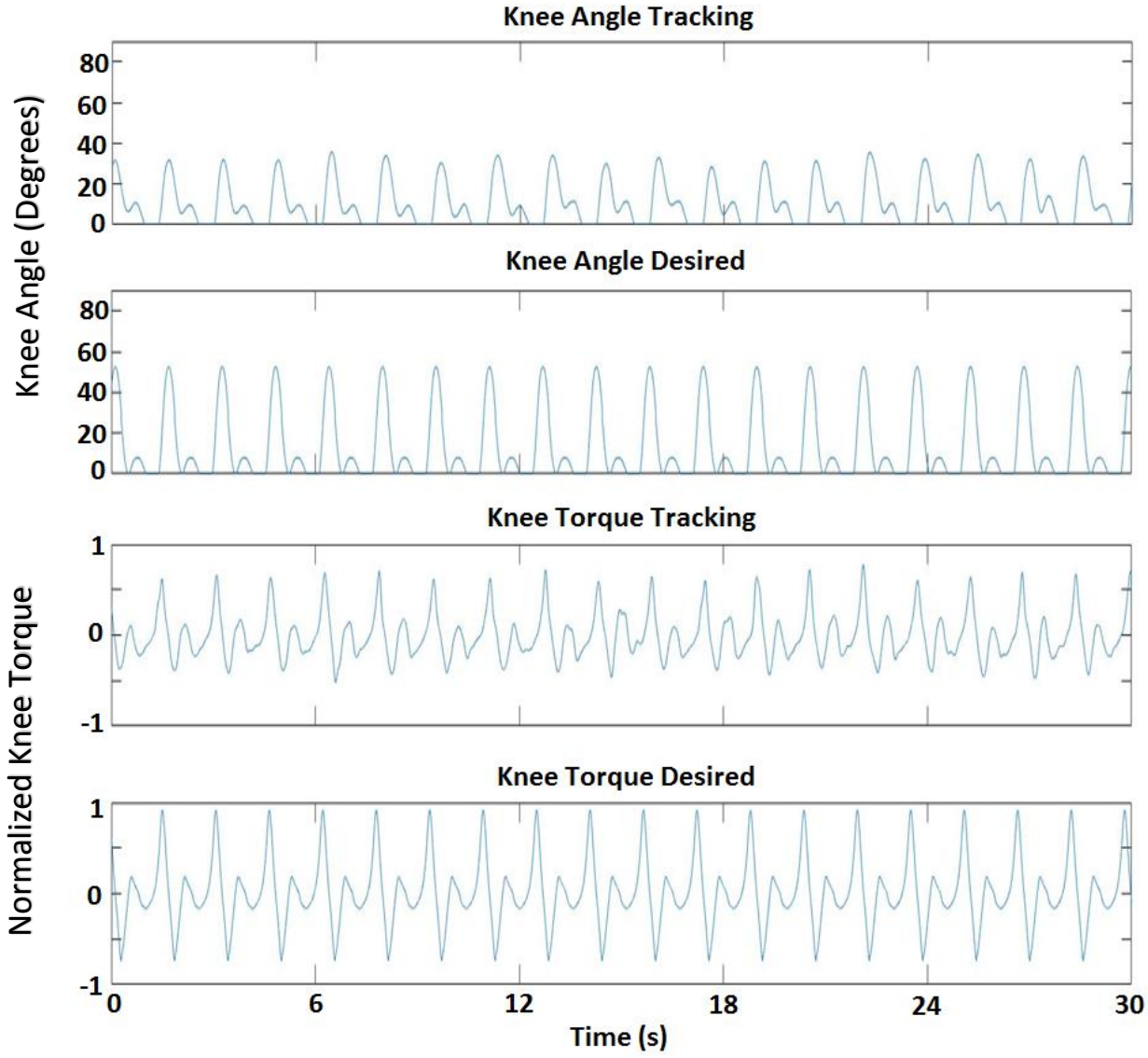

Figure 34: Plot showing actual versus desired spatial trajectories and actual versus desired torque trajectories for one motion tracking test while provided a spatial-only communication method.

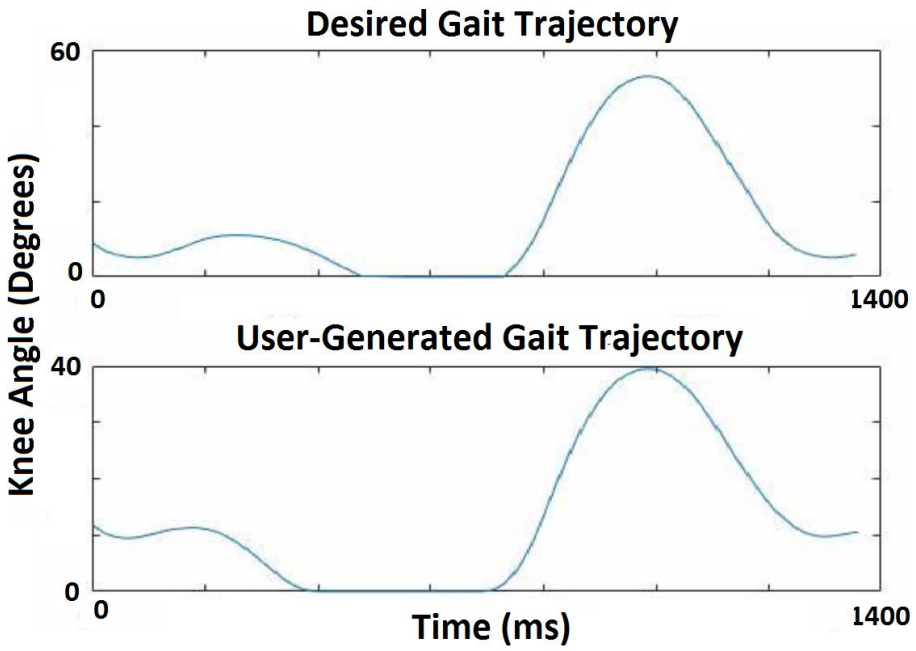

Figure 35: Plot of ensemble averaged desired gait trajectory and user-generated gait trajectory.

What was more surprising however, was the performance of the replication tasks. The replication task offered significant improvement over the control test. During the control test for motion replication, instead of having the test subject attempt to identify their speed, the user was asked to repeat a previously presented rate of motion (Figure 36). During these control tests, subjects demonstrated an accuracy of task replication of approximately 84%. Essentially, the test subjects found themselves replicating the prescribed motion within ± 0.4 mph. It was then hypothesized that the test subjects would not perform significantly differently than the control when only provided haptic feedback patterns to replicate. But, as the tests have demonstrated, the subjects performed with an accuracy that was significantly better than the control test, with a combined average accuracy of approximately 91% within ± 0.2mph. While this result was somewhat unanticipated, it is thought that this process may have something to do with prior

observations by this research group, wherein psychophysical phenomena affected motion-tracking accuracy (Canino, 2017).

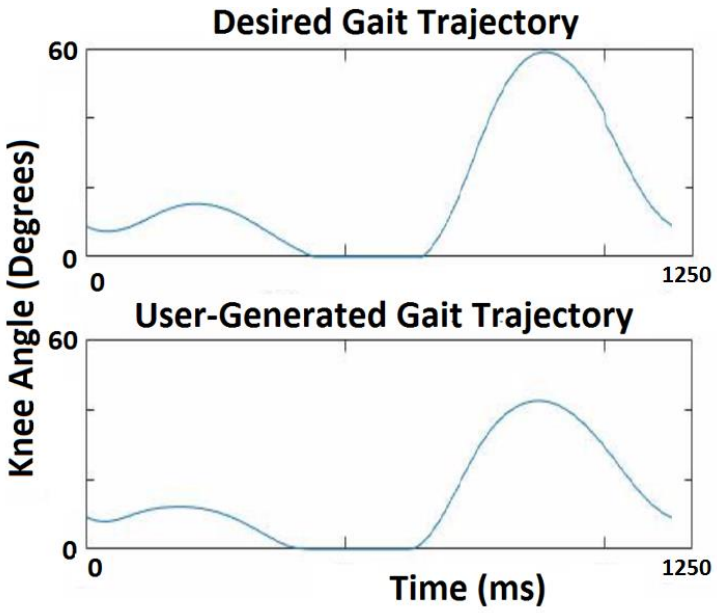

Figure 36: Plot of desired gait trajectory and user-replicated gait trajectory.

One could conjecture that the use of haptic stimulation on the forearm produces a greater perceptual acuity, due to the higher innervation density of mechanoreceptors located in the forearm, than what may be a lower perceptual resolution of lower limb motions (Ashmore, 1990). This is particularly interesting when considering placement of haptic feedback arrays for rehabilitation tasks. As described in section V.C, the forearm was chosen for these tests because of a desire to avoid neuropathy that is commonly found in tissue proximal to amputation, and also because the forearm possesses a higher innervation density of mechanoreceptors. This is in agreement with our hypothesis and the findings of other researchers, who have found that the forearm offers a valuable

location for haptic communication of virtual reality environments in paraplegics (Shokur, 2016).

It is also interesting to note that while both of the haptic feedback methodologies demonstrated no significant difference in performance, test subjects expressed qualitatively significant differences. Some subjects contended that the combined haptic scheme was disjointed, with the torque information being unnecessary and distracting. Others found that the torque information in the combined method was incredibly helpful and intuitive, and they preferred it over the spatial feedback alone. These preferential differences are important for consideration in future testing. Test subjects should experience both systems and choose whichever they prefer.

While coherence between the morphology of the subject's gait and the desired gait was of interest for understanding any differences between communication methodologies, there was no observable significant difference. The average disparity between subject generated gait waveforms and the desired waveforms likely has to do with the fact that the desired waveforms were heavily post-processed in order to create the gait loops. Though the effects of coherence is currently unclear, it is interesting to observe the ensemble averaged torque trajectories presented in Figures 37 and 38. In the instance where the subject is performing a motion tracking task (Figure 37), it is evident that the individual has very good morphological tracking of torque – including torque magnitude. Conversely, when looking at the torque following of the replication trials (Figure 38), it becomes evident that the individual is not beholden to any specific torque trajectory – and yet they are still able to obtain a similar gait morphology and step

frequency (Figure 36). This may have interesting implications in future analysis as subjects are able to accomplish the same knee kinematics with different EMG commands.

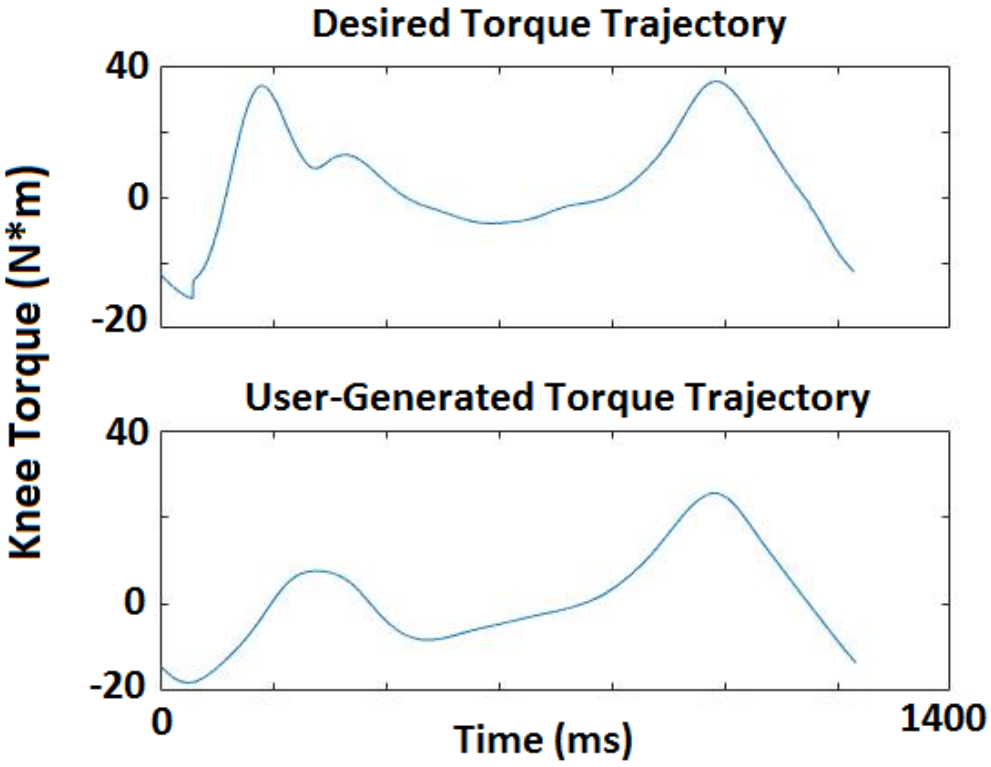

Figure 37: Plot of ensemble averaged desired torque trajectory and user-generated torque trajectory from motion tracking task shown in Figure 34.

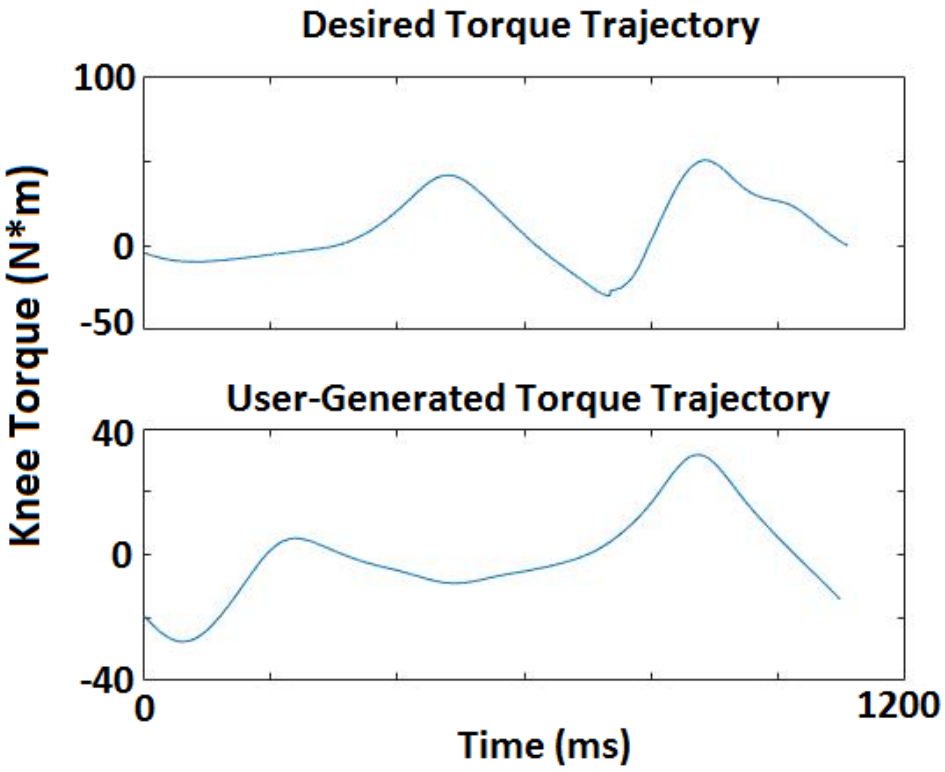

Figure 38: Plot of ensemble averaged desired torque trajectory and user-generated torque trajectory from motion replication task shown in Figure 36.

Based on the results here, the high resolution haptic feedback array provided an effective means of not only communicating kinesthetic information, but also of instructing users on how to move. This is particularly important when considering the haptic feedback device as a tool aimed at facilitating the rehabilitation process of lower limb amputees. This then led to the question: could one observe the benefits of using the high resolution haptic feedback apparatus when learning how to control the EMG-controlled powered-knee transfemoral prosthesis?

VII. Powered Prosthetic Gait Pattern Learning

A. Purpose

It was successfully demonstrated that the high resolution haptic feedback array can effectively communicate cadence-dependent knee trajectories that are reproducible by able-bodied subjects performing level treadmill walking. Building on the demonstrated ability to communicate information useful for gait modulation with the haptic array, the final objective was to combine this haptic system and stimulation architecture with the EMG-controlled knee prosthesis. The purpose of this study was to examine the effectiveness of the haptic array on the process of learning motor control strategies for the successful execution of gait motion trajectories the EMG-controlled powered transfemoral prosthesis. This would be conducted on two groups – one provided haptic feedback and one only provided visual feedback.

B. Protocol

A total of 12 subjects were tested in this study under IRB approval #18-04. Subjects were assigned to one of two test groups (N = 6) – one provided haptic feedback and one provided only visual feedback. Test subjects were chosen based on their previous inexperience with the EMG-controlled powered-knee prosthesis. This inclusion criteria was made due to the objective of this study, which was to observe the differences in learning motor control techniques with and without haptic feedback.

Seated subjects first had the EMG electrodes affixed to their dominant limb as detailed in (II.D) and the limb was then immobilized using a belt. The initialization and calibration protocol as detailed in (II.E) was then conducted. Subjects were given 30

seconds to briefly familiarize themselves with limb control before beginning the tests. During tests, subjects were presented a randomized gait trajectory from the gait library described in section VI.D for 35 seconds. This would be presented either via haptic feedback or visual feedback, depending on the subject's group assignment. The haptic feedback stimulation pattern used was the spatial architecture, chosen for its previously demonstrated efficacy, the simplicity of information being communicated, and because the foot would not experience foot-ground interactions that are required for switching in the combined scheme (section V.F.1). The visual feedback was provided via a scrolling overlay of real-time knee angle versus the desired knee angle trajectory. Presented one of these feedback modalities, the test subject then attempted to follow this trajectory via EMG-control of the powered prosthesis. EMG, knee angle, and knee torque data was then recorded for each trial, sampled at 1 kHz. Between each test, subjects were given 5 minutes of rest before attempting the next trial with a new randomized gait trajectory being provided. After 5 such trials, the test subject would have the EMG electrodes removed and all data collected was archived. This testing was repeated with 6 different subjects in each group.

C. Analysis

Gait patterns were analyzed using a combination of prior analytical methodologies. Patterns were analyzed for their frequency content, as described by VI.G, their coherence data, also as described by the MSC procedure outlined in VI.G, and finally the data was also analyzed for step-length. This was a new metric that was chosen for this task. For step-length analysis, an ensemble average would be performed on the desired gait trajectory and the trajectory generated by the user. The length of this

ensemble averaged trajectory was the effective length of time that it would take for an average stride. These step-lengths could then be compared via RMS error between the desired and actual trajectory. It was hypothesized that this would be a better metric for analyzing human gait. An example of step length comparison can be seen in Figure 39.

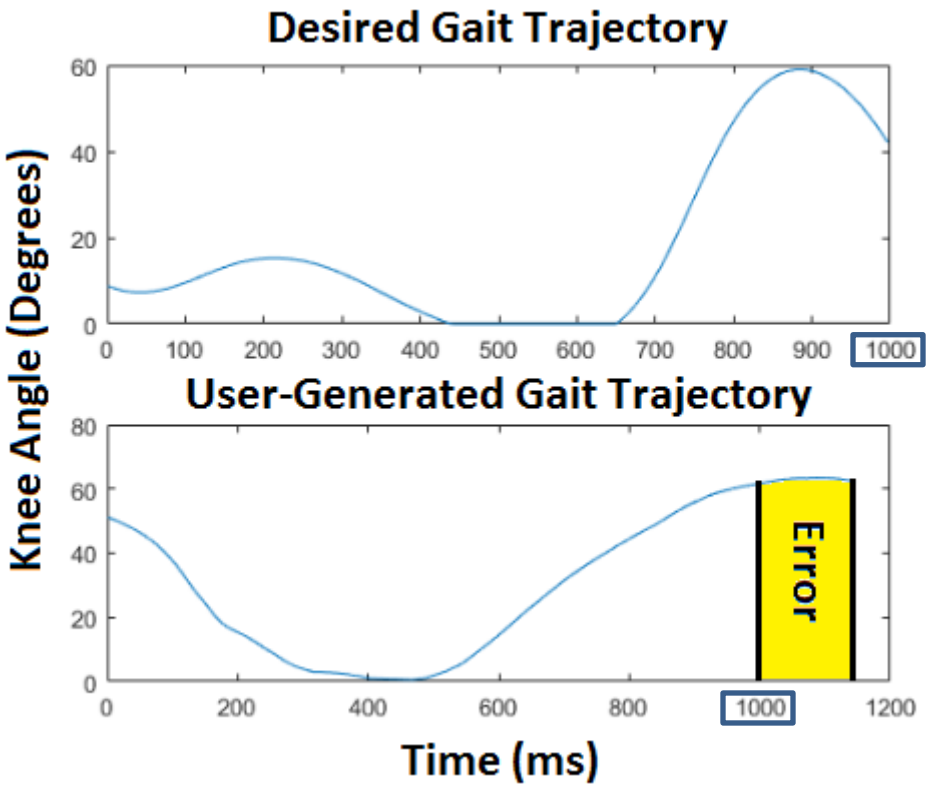

Figure 39: Plot showing comparison of desired trajectory step length versus generated step length and error in the user-generated step-length.

Comparisons of the frequency, coherence, and step-length content was conducted using ANOVA via SPSS analytical software. Note that this resulted in a great deal of analytical data, and while all of it will not be explored herein, its entirety can be found located in Appendix XI.A.4.

D. Results

A comparison of average frequency tracking for both groups is shown in Figure 50. Note that for each of the 5 trials, subjects with haptic feedback had a statistically significant improvement in frequency-matching accuracy when compared to visual feedback alone ($p = 0.0008$, 0.0004, 0.042, 0.0003, and 0.0004 respectively). It should also be pointed out that there was a statistically significant increase in frequency tracking performance over the course of the 5 trials for the group provided haptic feedback. This was not the case for the group provided only visual feedback.

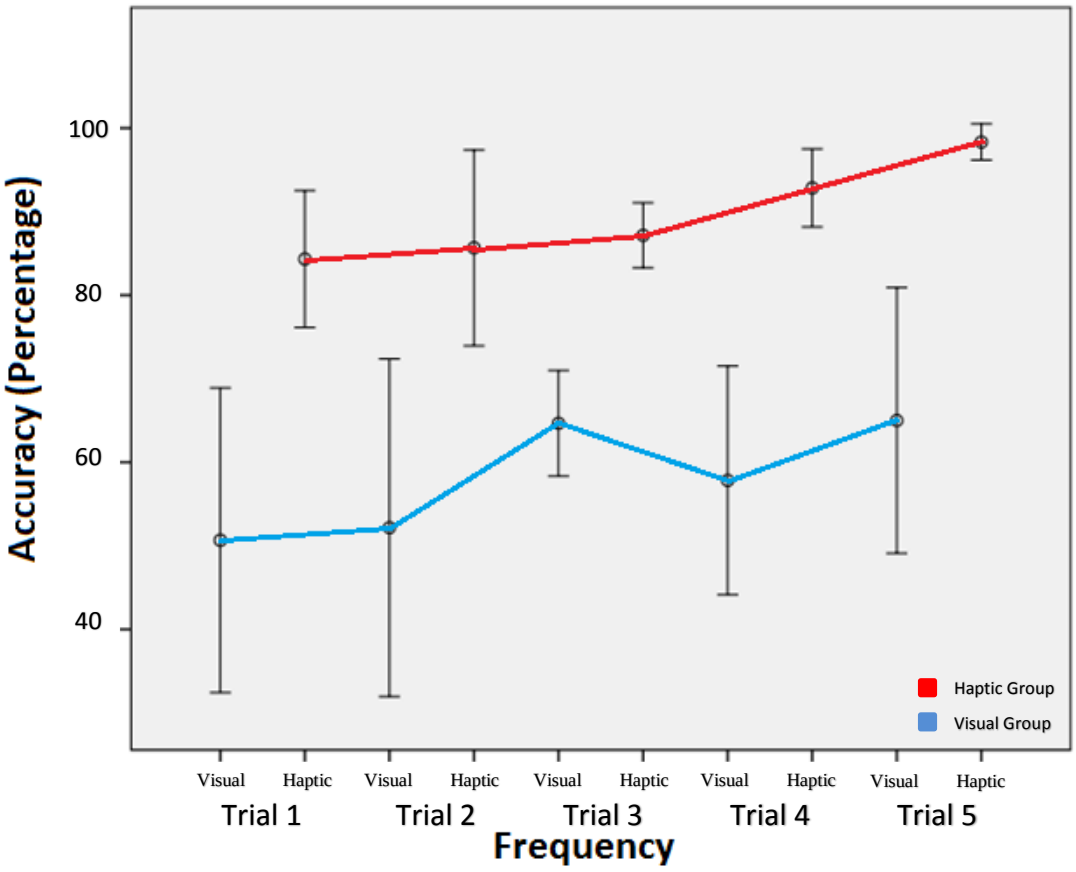

Figure 40: Plot of mean frequency data for visual (blue) versus haptic (red) learning.

The comparison of coherence data can be seen in Figure 51. There was no significant improvement in coherence performance between the two feedback schemes ($p = 0.109$, 0.677, 0.359, 0.191, and 0.343 for trials 1-5 respectively). Though it is important to note that there was a marked average performance increase observed in the haptic feedback scenario. It should also be noted that both schemes demonstrated an overall statistically significant increase in performance from the first trial to subsequent trials, indicative of learning and limb-control optimization.

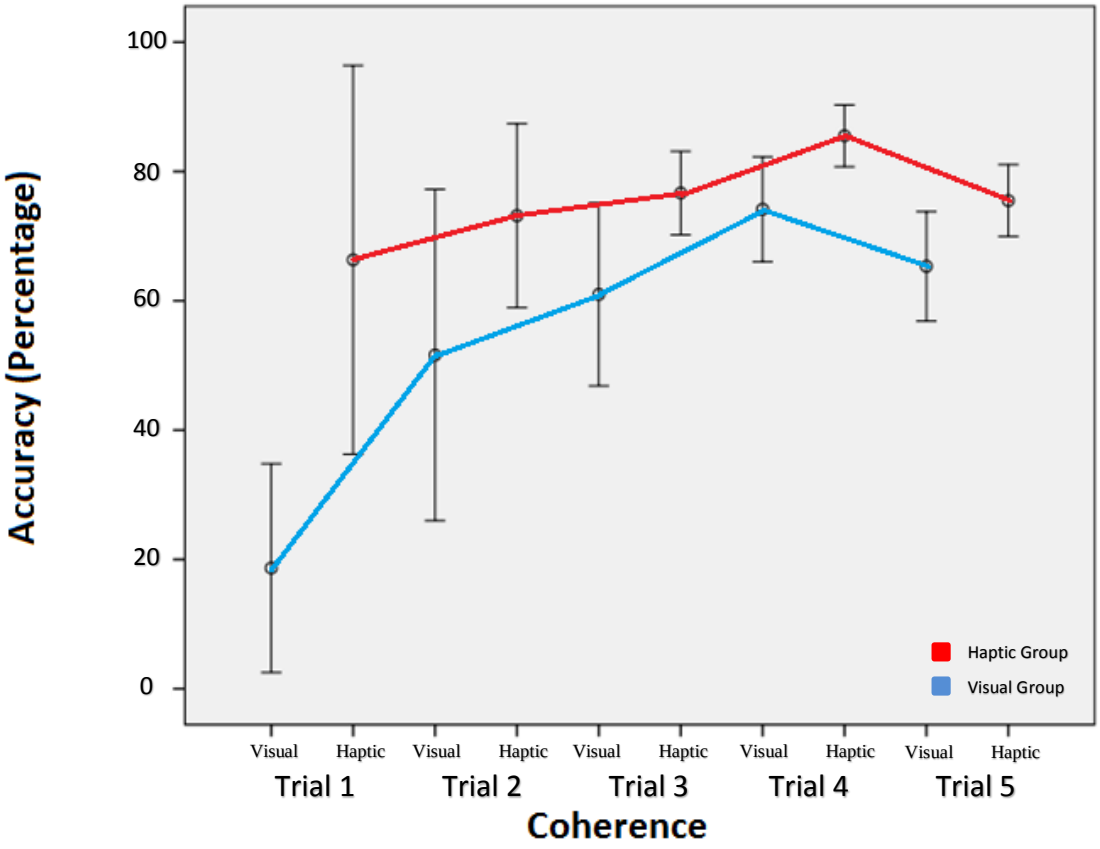

Figure 41: Plot of mean coherence data for visual (blue) versus haptic (red) learning.

Finally, the step-length data comparison can be observed in Figure 52. With step length, haptic feedback was found to perform statistically significantly better than visual feedback alone in trials 1, 2, and 5 with p values of 0.002, 0.012, and 0.019 respectively. Interestingly, haptic feedback did not provide a statistically significant improvement in trials 3 and 4 ($p = 0.574$ and $p = 0.505$ respectively). It should be noted that in the two trials where statistical significance was not observed, there was higher variance in the group that was only provided visual feedback. Unlike coherence, significant improvement in step-length accuracy was not observed for either group over the course of the 5 trials.

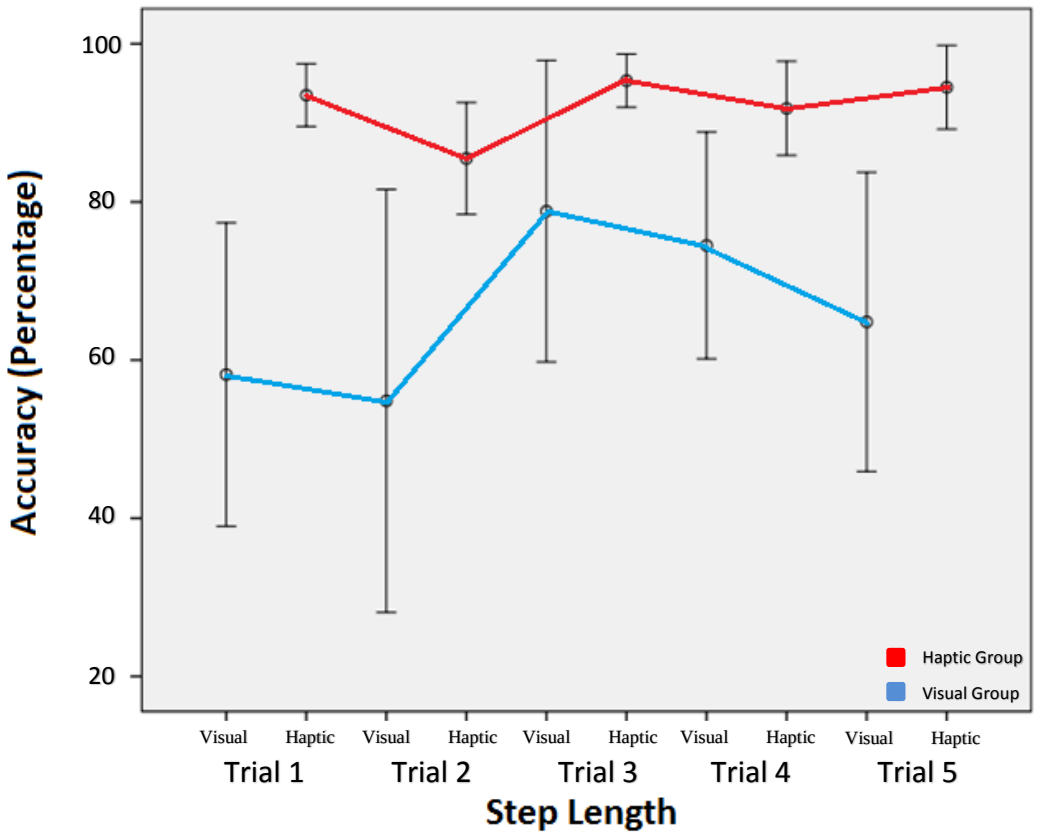

Figure 42: Plot of mean step length accuracy data for visual (blue) versus haptic (red) learning.

A. Discussion

From visual inspection of data trends, it is clear that implementation of the haptic feedback array had a meaningful impact on the learning process. This was also verified statistically, with the proper tracking of frequency content being significantly better when haptic feedback was used in the learning process. Because the haptic feedback system was essentially providing a rhythmic pacing, it would make sense that the user would have a better frequency tracking. Also interesting from a morphological standpoint of Figure 50 the frequency tracking accuracy positively trends during the learning process when haptic feedback is incorporated, while it is not clear that there was marked progress in visual training alone. This was also in agreement with qualitative observations by test subjects, wherein they conjectured that they felt like they were improving with the haptic feedback, while the visual group often lamented their incapability of properly gauging the rhythmic motions.

Analysis comparing coherence of user-generated trajectories to that of the desired trajectories was again not clearly beneficial from a comparative standpoint. This has to do with the large variances observed in coherence data across test subjects. While the coherence data was unable to demonstrate that haptic feedback offered a significant improvement, the results of Figure 51 do qualitatively demonstrate the marked improvement in performance given by the haptic feedback system. It is hypothesized that continued testing should allow for a decrease in variance and a more statistically robust comparison of the two. An important observation that can be gleaned from the coherence data is the fact that learning was taking place. This can be conjectured from the way that

the mean coherence performance increases with each sequential test. It is interesting to note that the haptic feedback had less of an improvement over time, but subjects started at a higher average coherence than their visual cohorts. This phenomenon could best be described as a flattening of the learning curve, which might be a valuable insight into the benefits of using a haptic feedback system. That is to say, though haptic feedback alone might not necessarily lead to a marked improvement over conventional rehabilitation techniques in the long-run, it may get patients to a stable state of rehabilitation significantly faster.

Analysis of step-length was of good value, offering a unique insight into the benefits of using haptic feedback. Note in Figure 52 that subjects in the visual group provided step-length data with a high variance, so much so that it skewed the analytical comparisons of tests 3 and 4. While statistical analysis demonstrated that the step-length performance was significantly improved in the haptic feedback group for trials 1, 2, and 5, the same could not be said about trials 3 and 4 due to this variance. Looking at the step-length morphology for both groups, it is interesting to note that there was a sharp increase in step-length performance between trials 2 and 3. Qualitatively, this is the point where test subjects have begun to optimize their EMG-control of the powered prosthesis. Again, as with the coherence data, the step-length data for the haptic feedback group did not vary as much between trials. The haptic feedback group essentially started at a markedly improved step-length accuracy and continued to improve up to trial 3, wherein the subject stabilized about an average step-length accuracy of around 90%. This was in contrast to the visual group, where there were more dramatic changes in subject performance with seeming down-trend begging by trial 5. It should be stated that subjects

of the visual group appeared to continually try and change their control technique in an effort to optimize performance, whereas the haptic group expressed that they were comfortable with their control technique after trial 3. This seeming down-trend observed at trial 5 in the visual feedback group may then be indicative of how the traditional learning process may take more time than that enhanced by haptic feedback. That is to say, visual feedback yielded more uncertainty in subject control techniques while haptic feedback guided the user into an optimized control technique. This was also qualitatively observed by test subjects in the haptic feedback group saying that they were confident in their ability to control the limb well, while the visual feedback group still felt like they had to work on their control techniques.

Example trials of one visual-group subject and one haptic-group subject are presented in Figures 43 – 47 and Figures 48 – 52 respectively. These subjects were not chosen because of any notable performance or behavior; their performance was considered average for their respective groups. These sample trials are shown in an effort to demonstrate the quality of limb control that could be obtained within a short window of training when provided only visual feedback or haptic feedback.

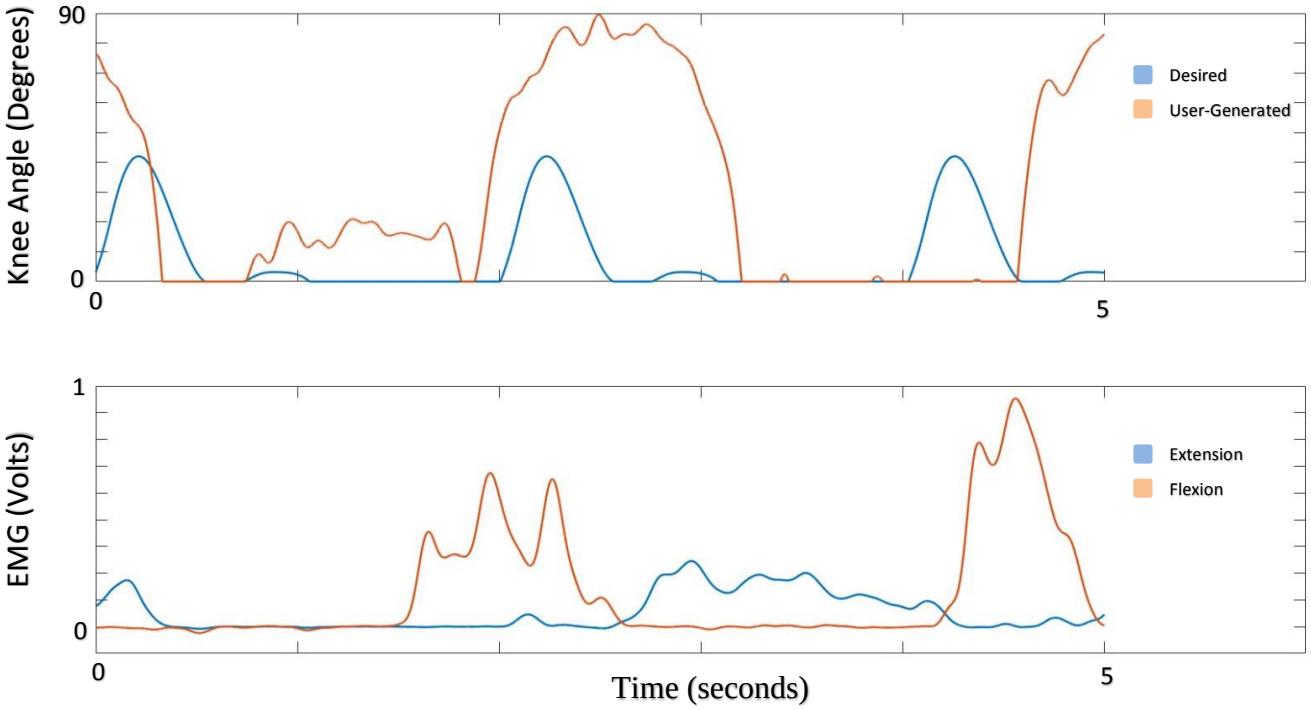

Figure 43: Plot of visual subject, trial 1.

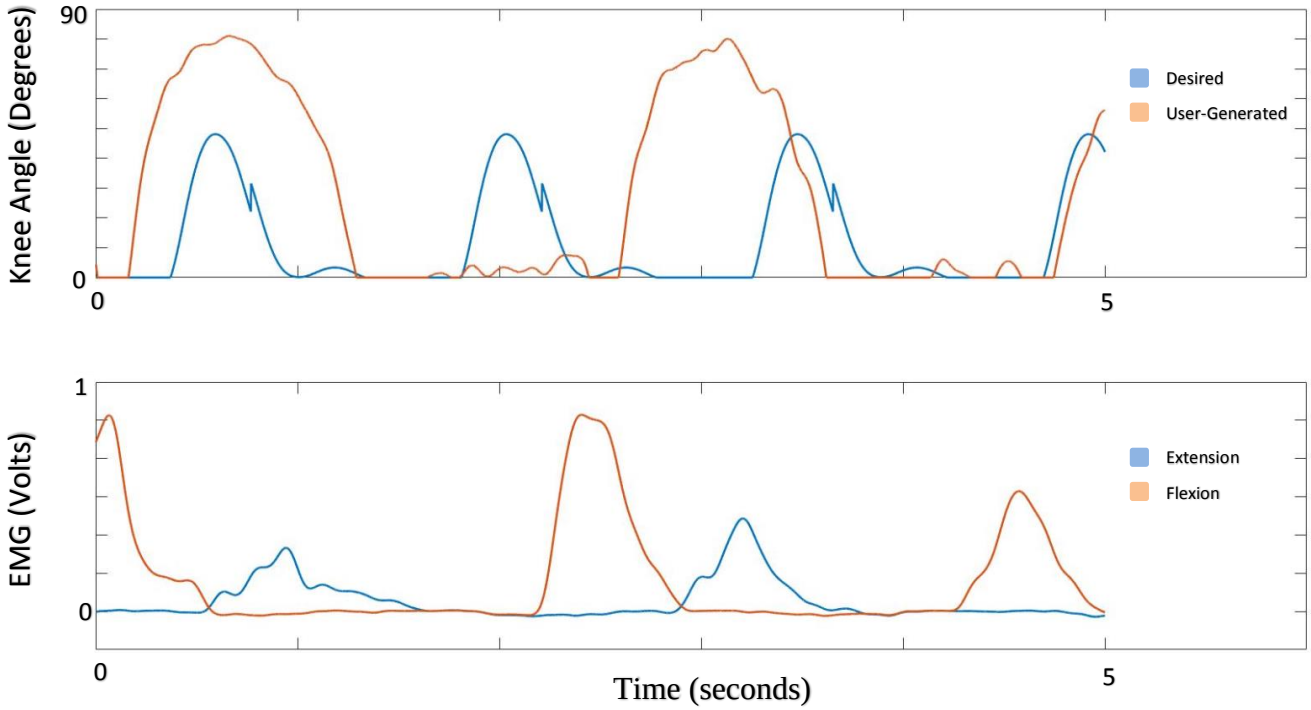

Figure 44: Plot of visual subject, trial 2.

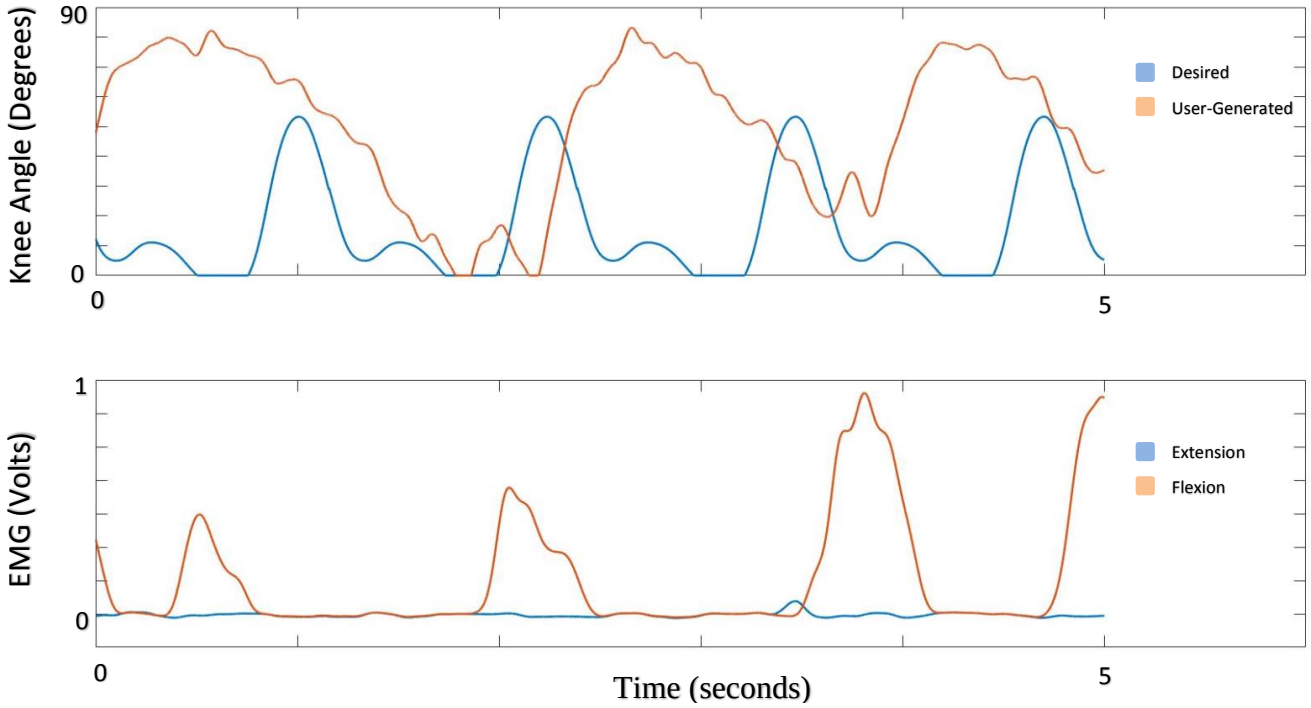

Figure 45: Plot of visual subject, trial 3.

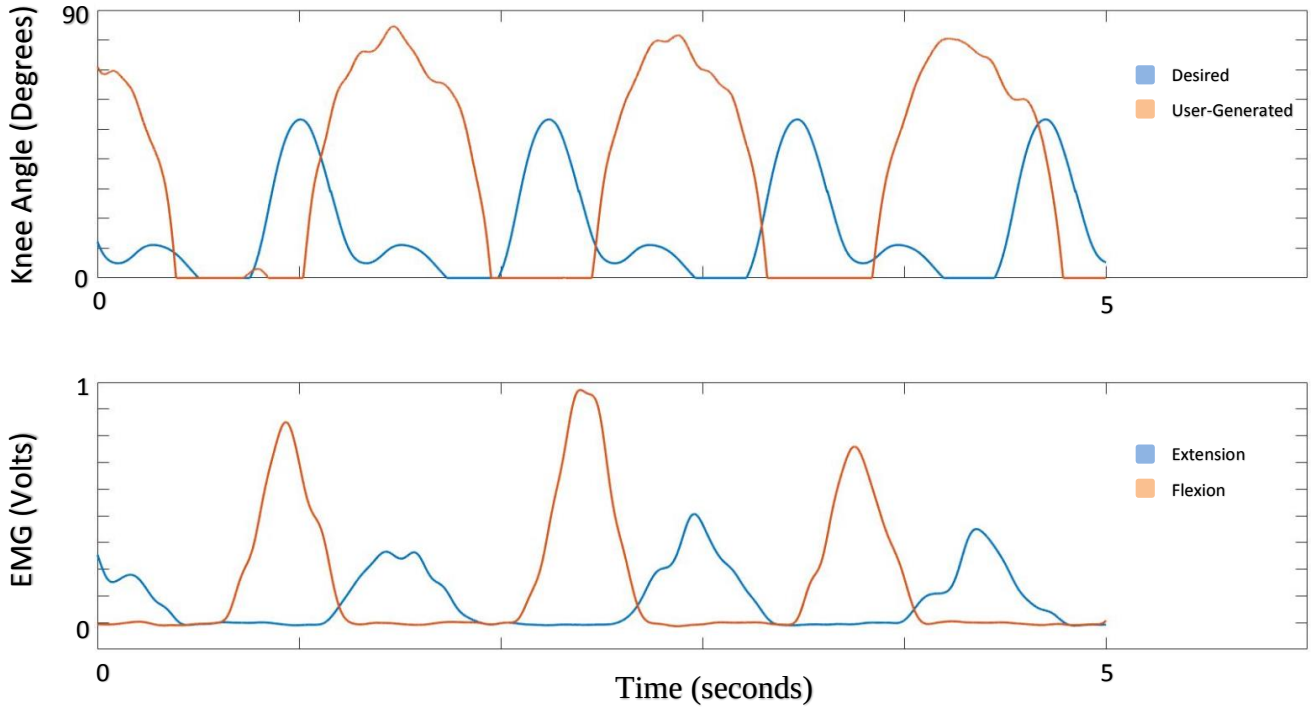

Figure 46: Plot of visual subject, trial 4.

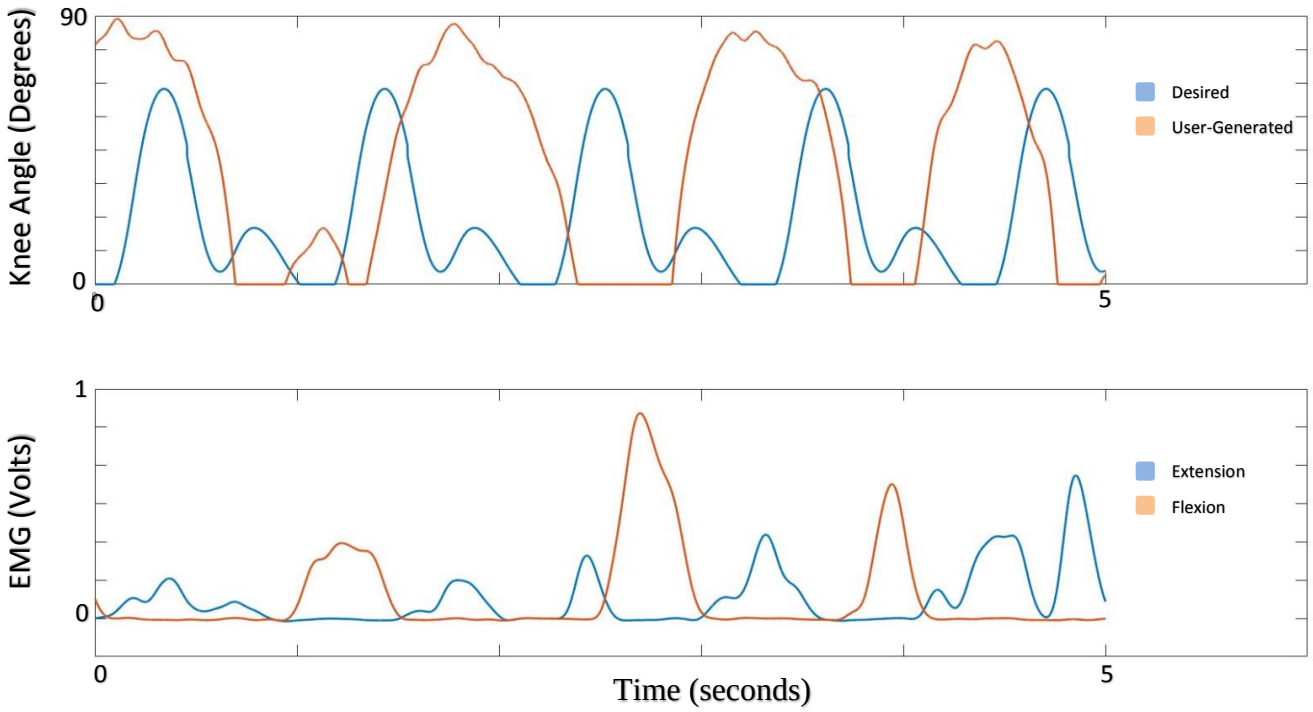

Figure 47: Plot of visual subject, trial 5.

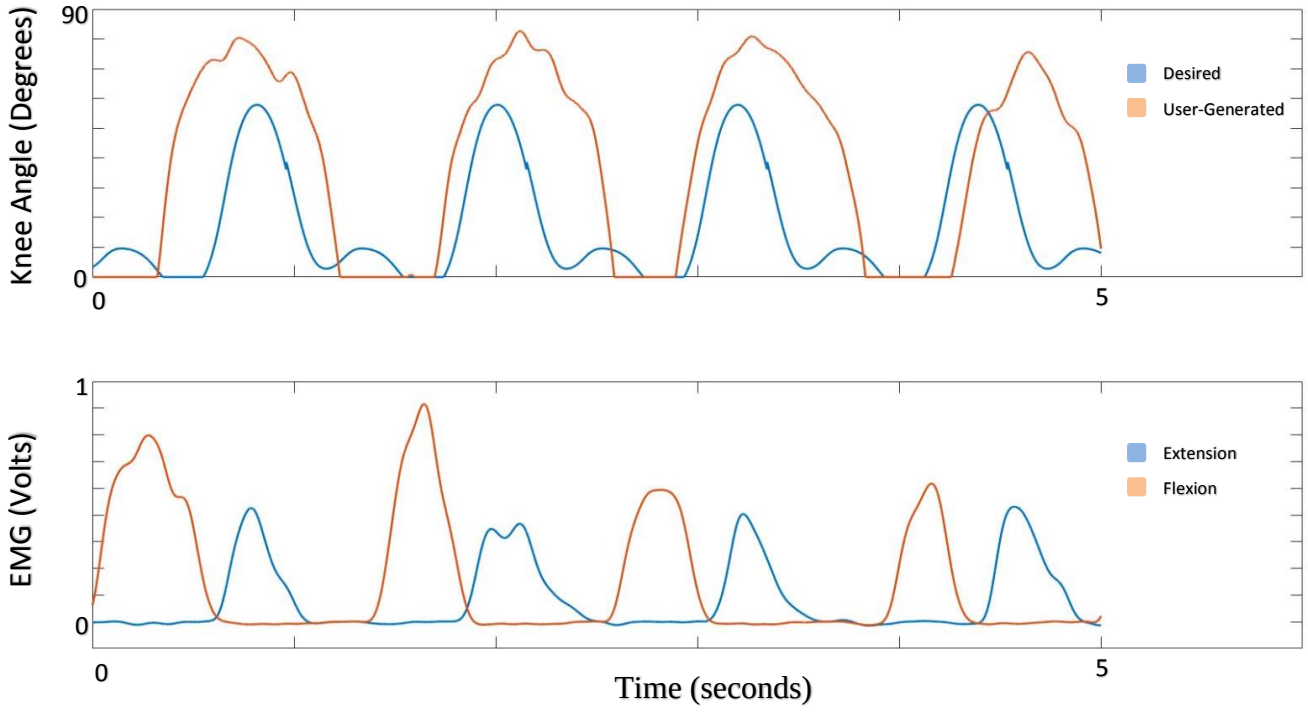

Figure 48: Plot of haptic subject, trial 1.

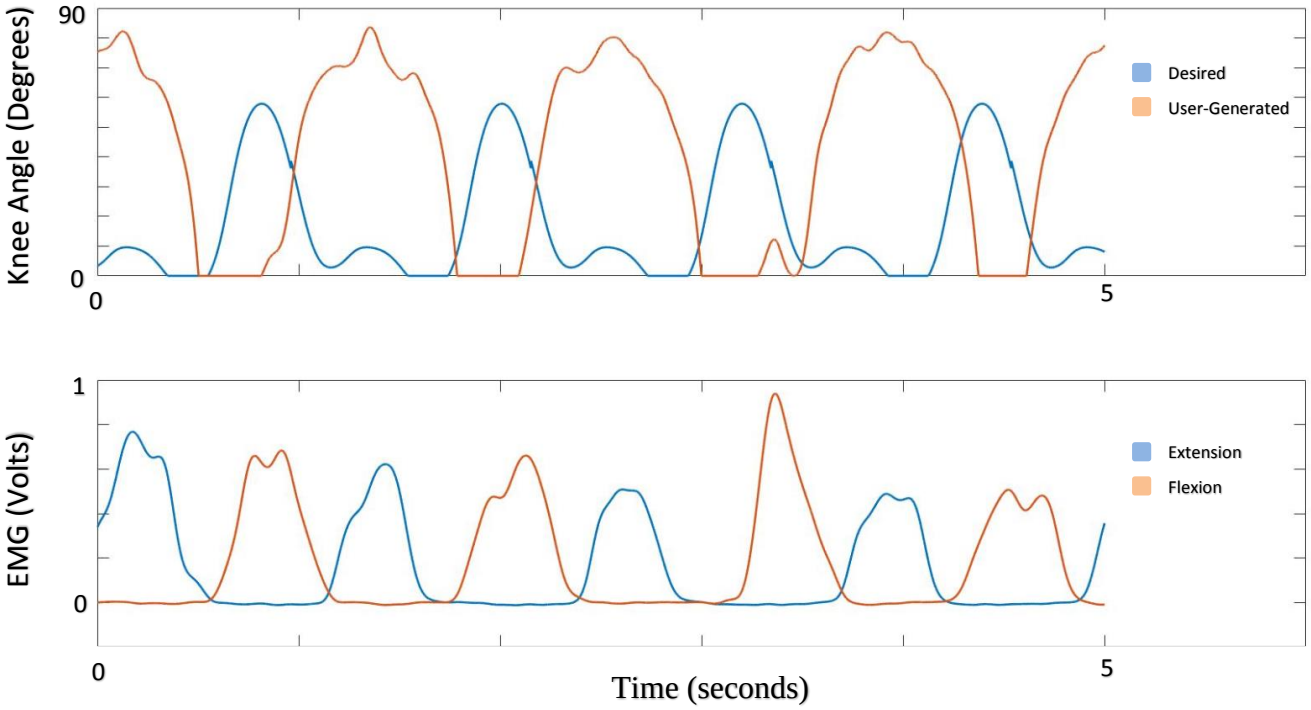

Figure 49: Plot of haptic subject, trial 2.

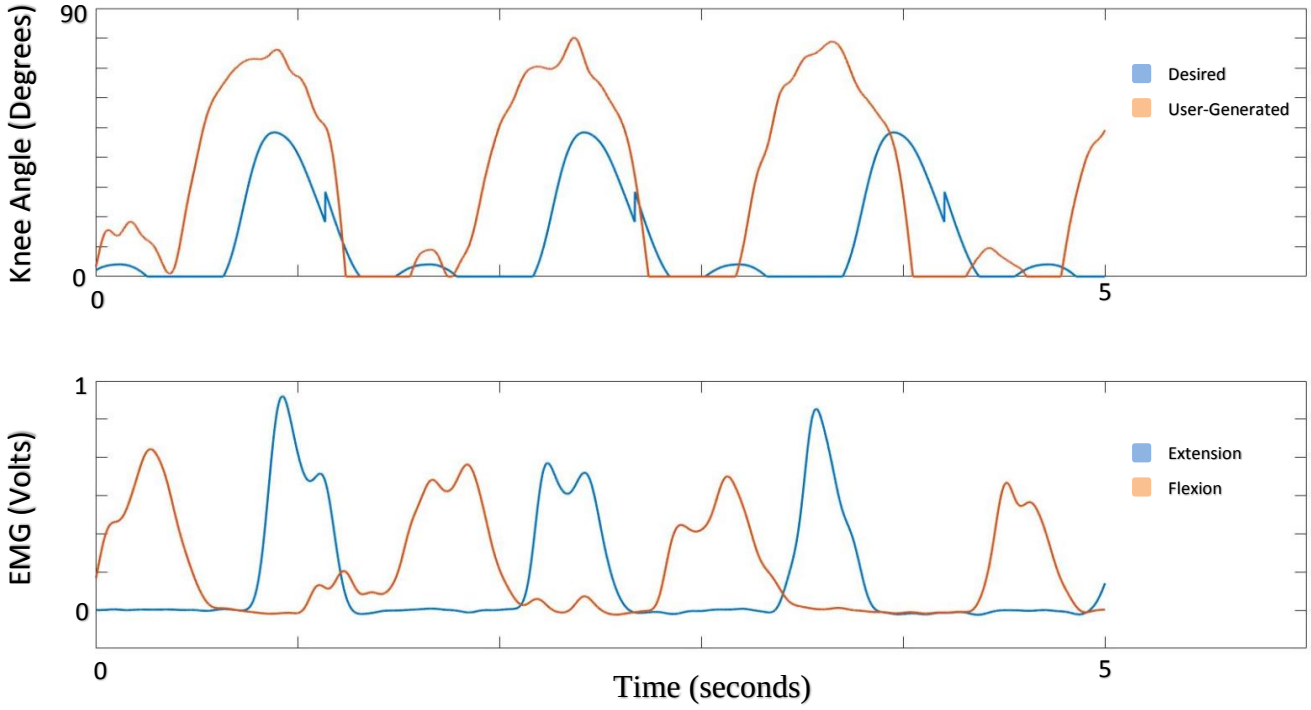

Figure 50: Plot of haptic subject, trial 3

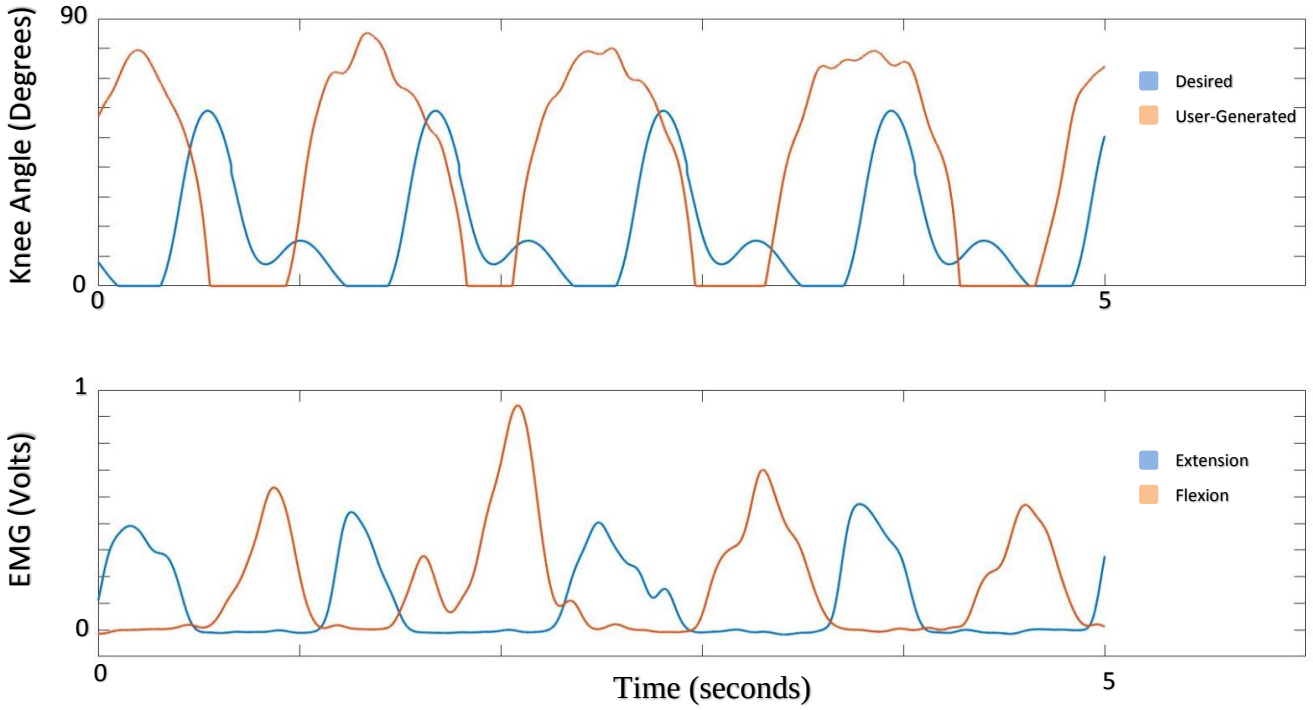

Figure 51: Plot of haptic subject trial 4

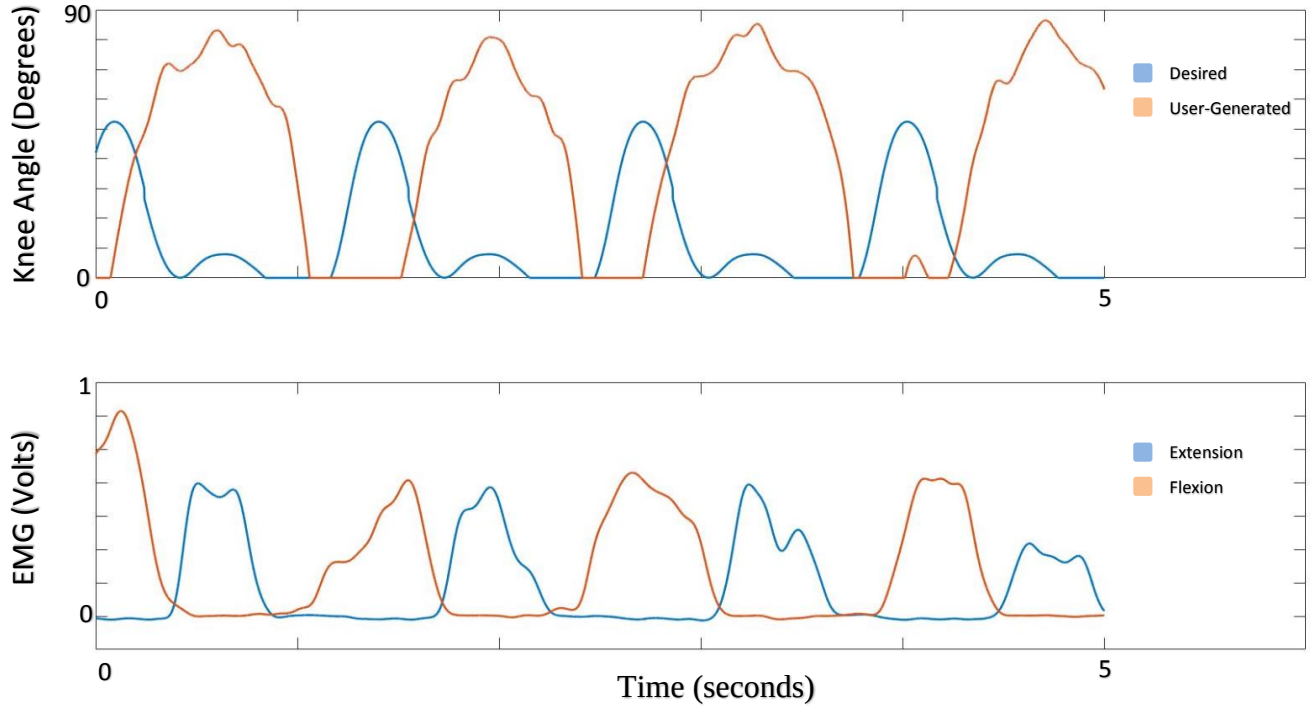

Figure 52: Plot of haptic subject trial 5

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Looking at the trial plots for the sample visual and haptic subject trials (Figures 43 – 52), the benefits of haptic feedback is readily apparent. The subject in the visual trials demonstrated early difficulty in the control of the limb (Figure 43), which slowly developed into a somewhat efficacious control strategy by the final trial (Figure 47). But even this final performance is relatively poor when the ensemble averaged data is observed in Figure 53. Note that while the subject does produce an average motion akin to a desirable trajectory, the step length of the produced motion is nearly double that of the desired trajectory.

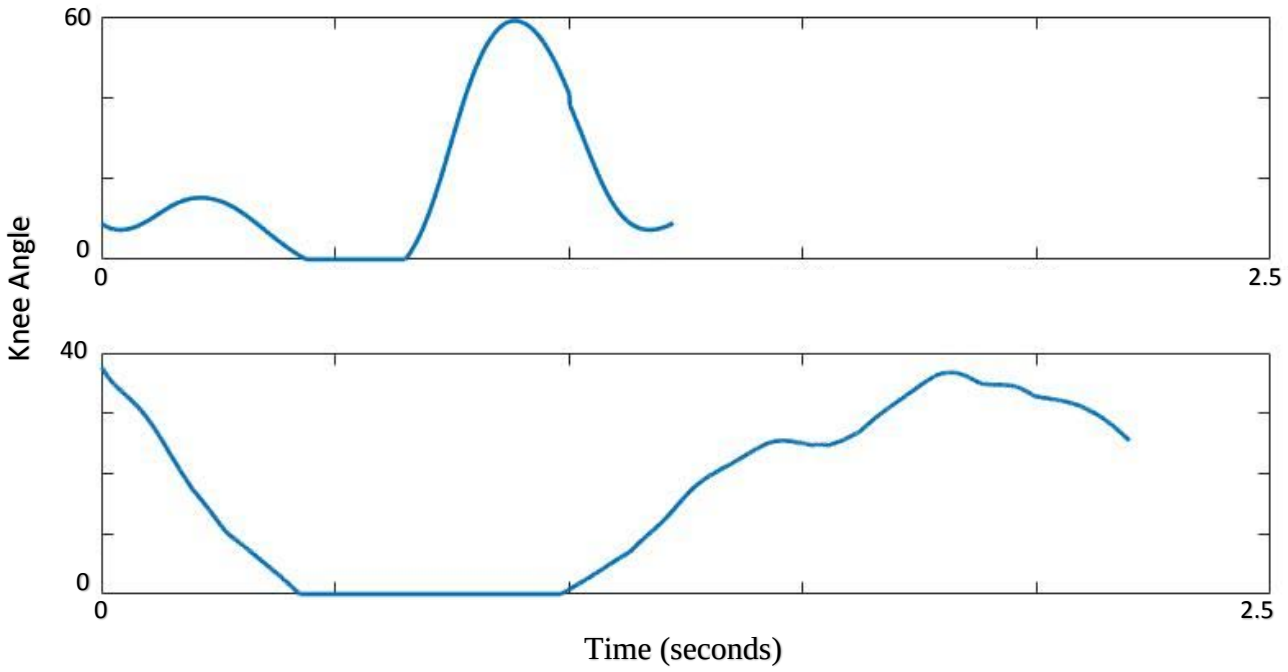

Figure 53: Plot of ensemble averaged visual tracking of knee angle originally shown in Figure 47.

Comparatively, the subject provided haptic feedback demonstrated a control technique that was at least comparable to the visual-subject's 5th trial during their very first trial with the limb (Figure 48). This early competence in control technique led to the subject attempting to better refine their fine-motor control of the limb. This can be

particularly evident in Figure 50, where the test subject can be observed attempting to obtain the small knee-flexion event that occurs during the transition from heel contact to stance phase. Ensemble averaging of the data presented in Figure 50 shows a produced motion that was both morphologically similar to the desired trajectory while also being of similar step length (Figure 54). This greatly demonstrates the capacity that the high resolution haptic feedback array had for communicating not only the large knee angle changes during the swing phase, but also the small angle changes that occurred during the transition into stance phase.

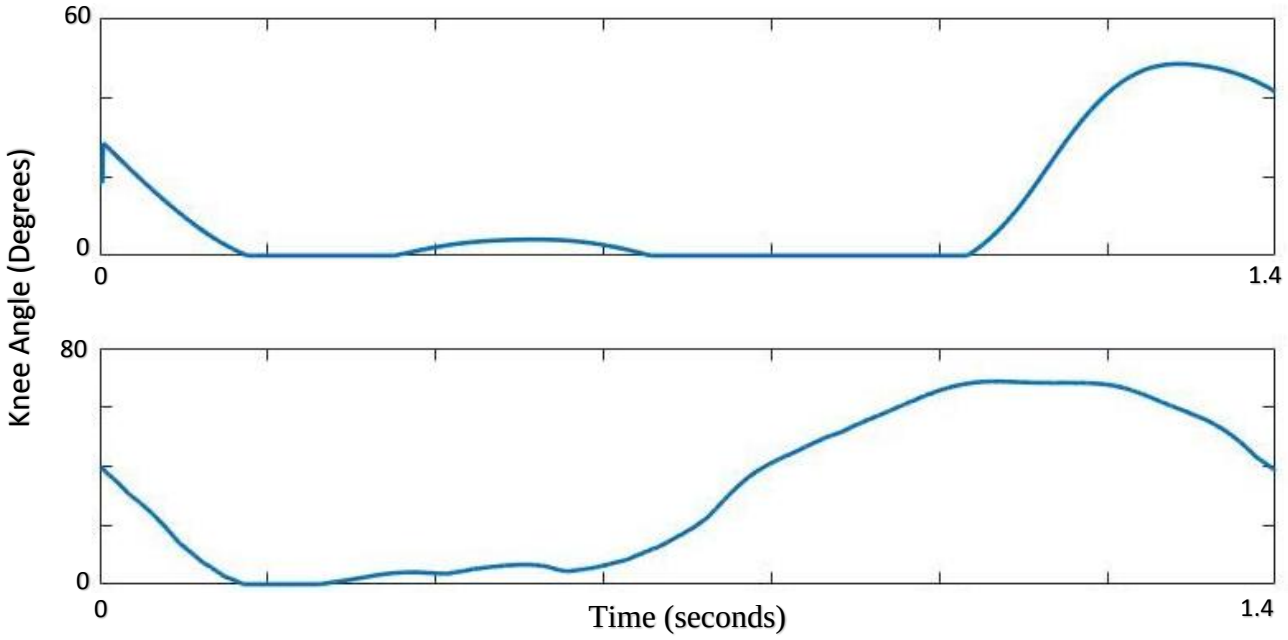

Figure 54: Ensemble averaged haptic tracking of knee angle originally presented in Figure 50.

This experimentation in motor control and haptic response did lead to the subject sometimes losing track of the communicated pace (as in Figure 49), but they were able to quickly correct and regain the appropriate control scheme for the desired trajectory. In Figure 52, the 5th trial conducted by the haptic subject, the subject attempted to follow the

trajectory by responding to the haptic architecture in an almost completely inverted fashion. But even with this unique motor control strategy, the subject was still able to perform the desired motion, as demonstrated by the ensemble averaged data shown in Figure 55. This experimental control strategy had merely phase-shifted their trajectory, while still maintaining good morphology and step length.

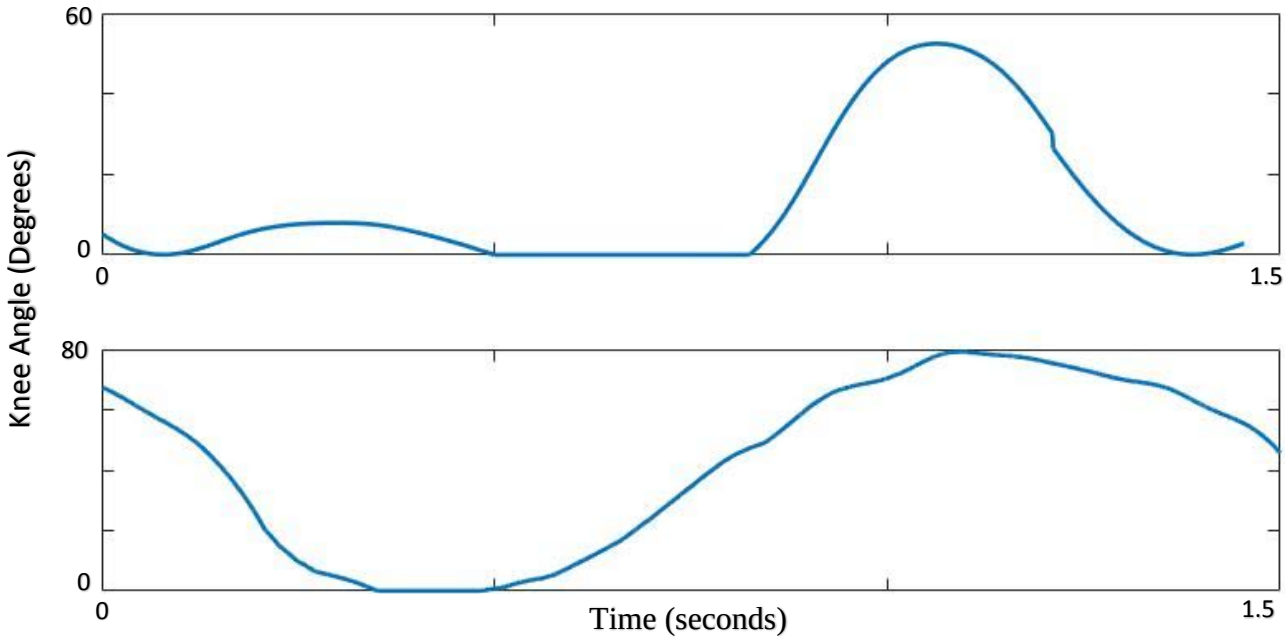

Figure 55: Ensemble averaged haptic tracking of knee angle originally presented in Figure 52

Combining the EMG data of the sample visual and haptic test subjects into Figures 56 and 57, it becomes easier to observe the benefits of using haptic feedback for learning powered prosthesis motor-control techniques.

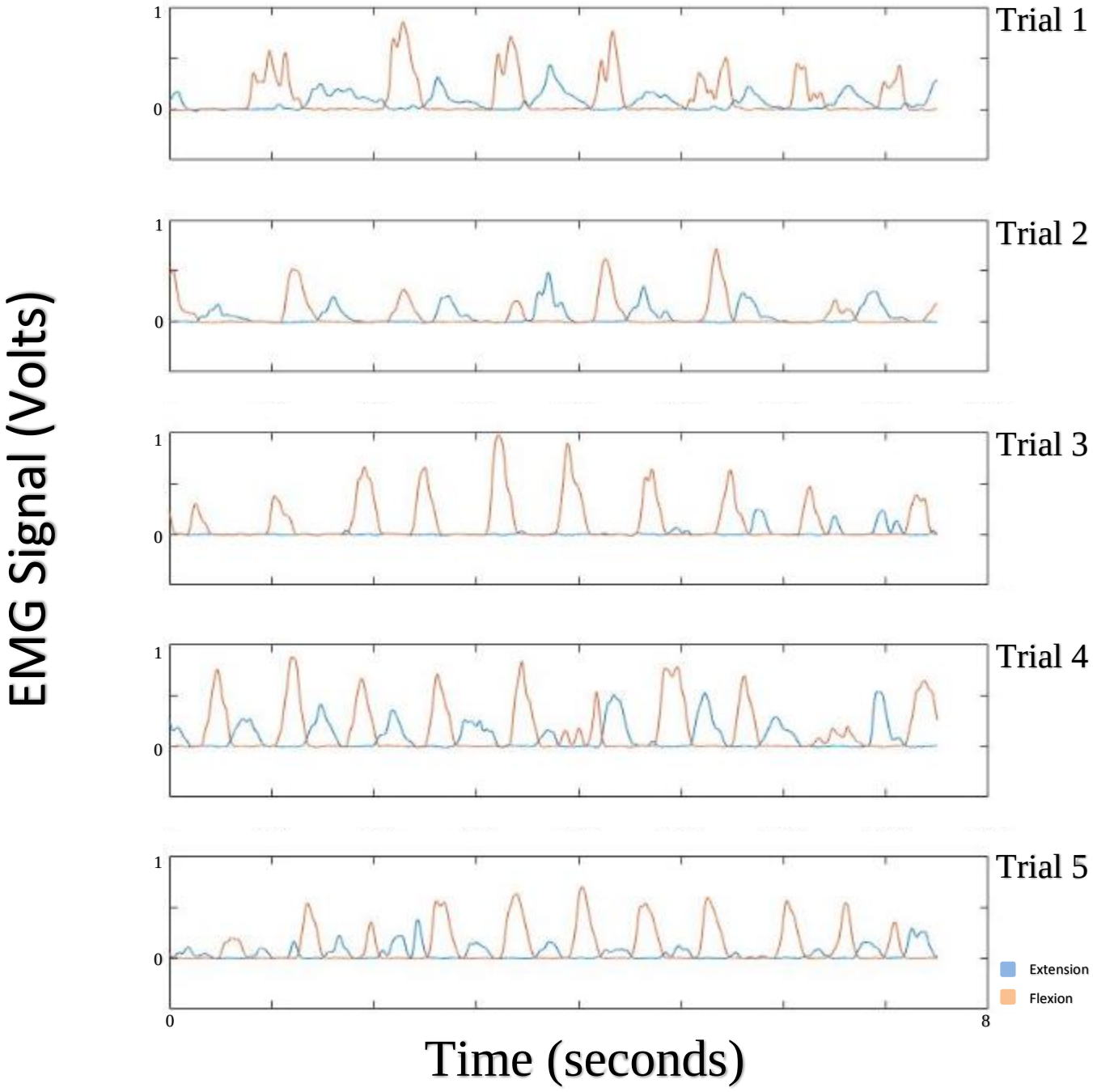

Figure 56: Compiled EMG control for visual-subject presented originally in Figures 40-44.

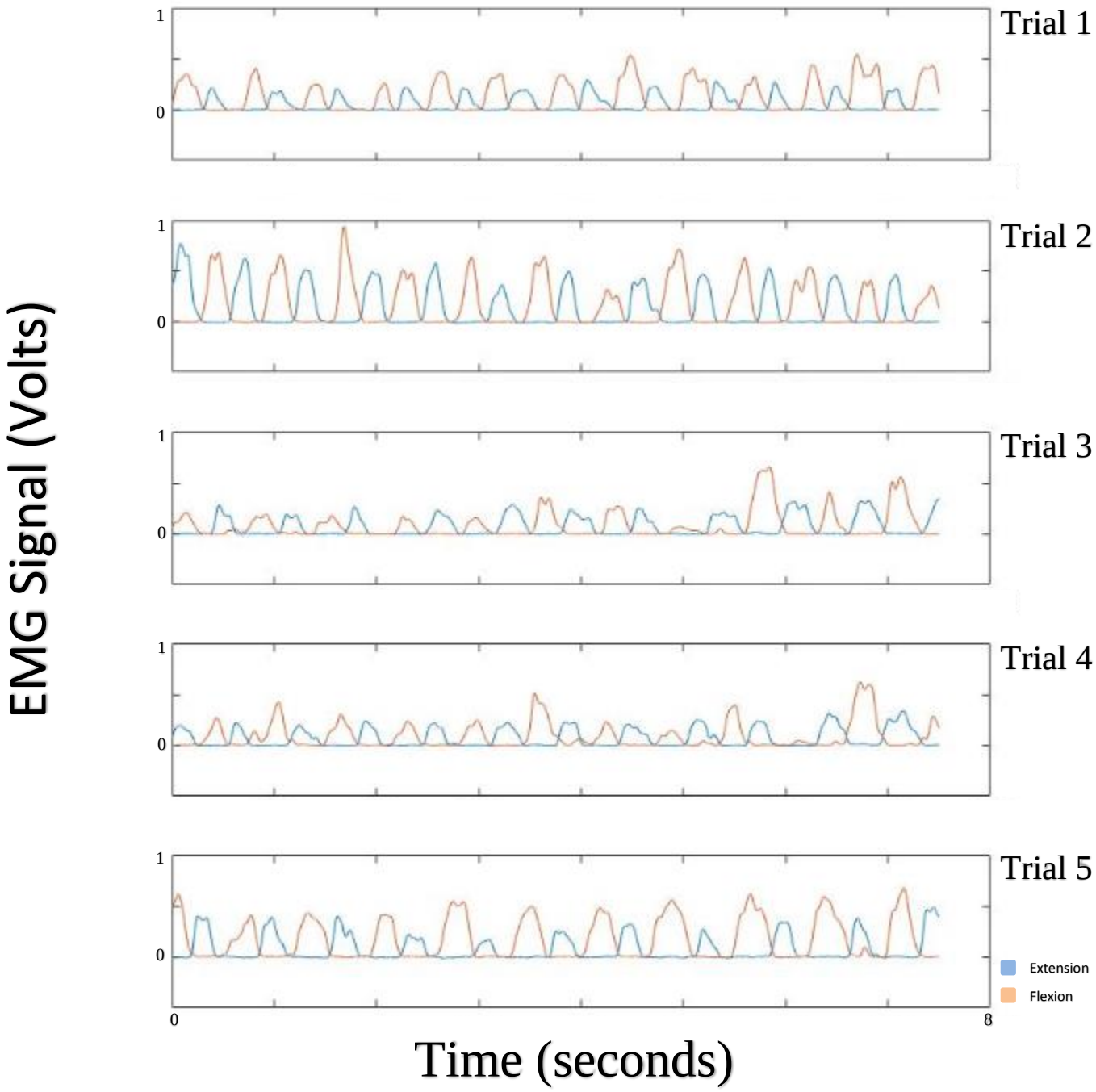

Figure 57: Compiled EMG control for haptic-subject presented originally in Figures 45-49.

Note in Figure 57 how the subject provided haptic feedback exhibited a consistent and rhythmic muscle-contraction pattern for controlling the limb (alternating flexion and extension), even when experimenting with different control strategies. This rhythmic

contractile control might have been crucial for the generation of the desired trajectory, shown by the ensemble averaged knee angle tracking of another subject provided haptic feedback (Figure 58). This consistency in rhythmic muscular agonist-antagonist contraction was only observed in the haptic feedback group.

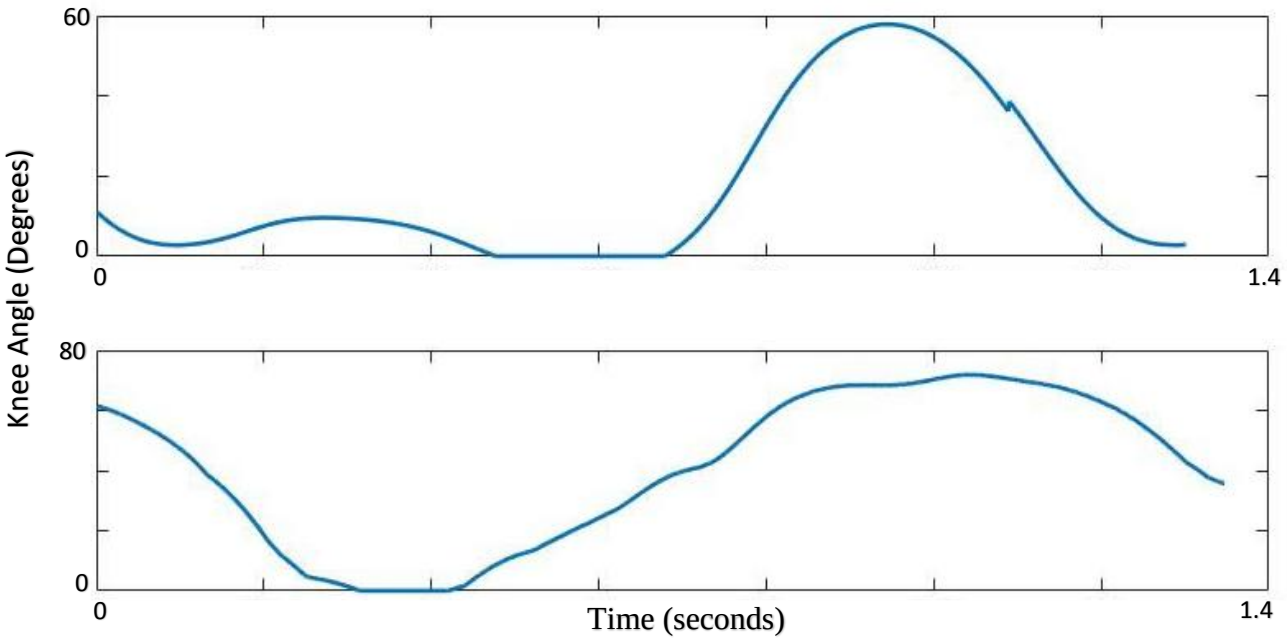

Figure 58: Ensemble averaged plot of haptic tracking of presented knee angle.

This is in contrast to the subject provided only visual feedback (Figure 56), who exhibits non-uniform muscular contractions with no discernible control pattern, even by the 5th trial. The effects of these non-rhythmic muscular contractions can best be visualized in Figure 59, which shows an example ensemble averaged trial for another subject provided only visual feedback. Note how the overall average generated trajectory was very different from the desired knee angle trajectory, not only in the matching of morphological landmarks, but also in the disparate step length. This was the standard observation in the visual-only group.

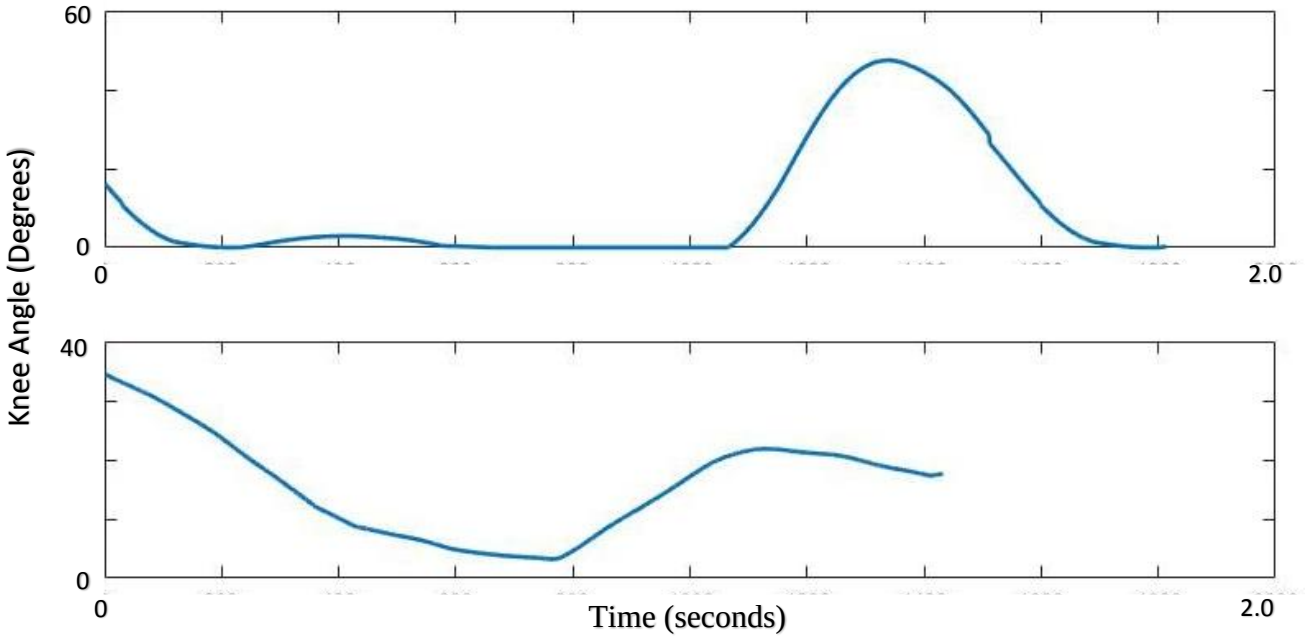

Figure 59: Ensemble averaged plot of visual tracking of presented knee angle.

While it has been shown that the learning process was enhanced by the incorporation of haptic feedback, it is not entirely clear how this process was enhanced and how to best leverage haptic feedback in the rehabilitation process, i.e. should gait-rhythm training be provided only for the first few weeks of rehabilitation, before switching over to a real-time kinesthetic communication system? It is then important that data collection be continued on the learning process. During prior studies, new test subjects were put through a simple training process but data was not collected. It will be important for future work that all subjects be trained via a prescribed protocol that allows for collection of further learning data, which would then allow for more statistically stringent evaluation of this learning process.

VIII. Conclusion

A. Overview

This study began with the experimental validation of haptic feedback as a means of communicating trajectory information in the one-degree of freedom control of an EMG-controlled transfemoral prosthesis. From these experiments, it was understood that while the haptic feedback system could convey complex information, it was still limited in its spatial resolution and capacity to better communicate more complex real-time kinesthetic information that would be experienced by the powered prosthesis.

Because of this, a new high resolution haptic feedback array was constructed and evaluated in its capacity to supersede the prior haptic feedback system's ability to convey spatial information about a knee angle. It was determined that the increase of spatial resolution in the new array allowed for the communication of knee angles with a two-fold reduction in knee angle perception error. With this evaluation of the system, it was important to then attempt to communicate advanced kinesthetic information akin to those seen in locomotor tasks.

This led to the haptically guided tracking and replication tasks performed by able-bodied subjects. These tests demonstrated that the system could not only effectively communicate gait trajectories for motion tracking, but that the system could also allow for subjects to replicate previously experienced motions while only being provided their limb's real-time kinesthetic information via haptic feedback. The latter test yielded the most surprising results, wherein subjects appeared to be able to perceive the haptic feedback system to a greater degree of accuracy than their own lower limbs' proprioceptive sense. From these tracking and replication tasks, it was clear that subjects

could be coaxed into following prescribed gait trajectories with a high degree of accuracy. It was then questioned as to whether or not this system could be used to enhance the learning experience of controlling an EMG-controlled powered-knee prosthesis.

Finally, there was experimental evaluation of two test groups, one where haptic feedback was provided and another where only visual feedback was provided. These two groups of individuals had no prior experience in controlling the prosthetic limb and were tasked with following gait trajectories either presented with haptic or visual feedback. It was found that the haptic feedback system offered a significant improvement in performance over those being provided only visual feedback, with marked performance benefits observed in frequency content, coherence, and step-length. From this, it can be stated with certainty that haptic feedback should be strongly considered in not only the day-to-day use of lower limb prosthetics, but also as a learning tool in the rehabilitation of lower limb amputees. A flow-chart, showing an overview of this work, is presented in Figure 60.

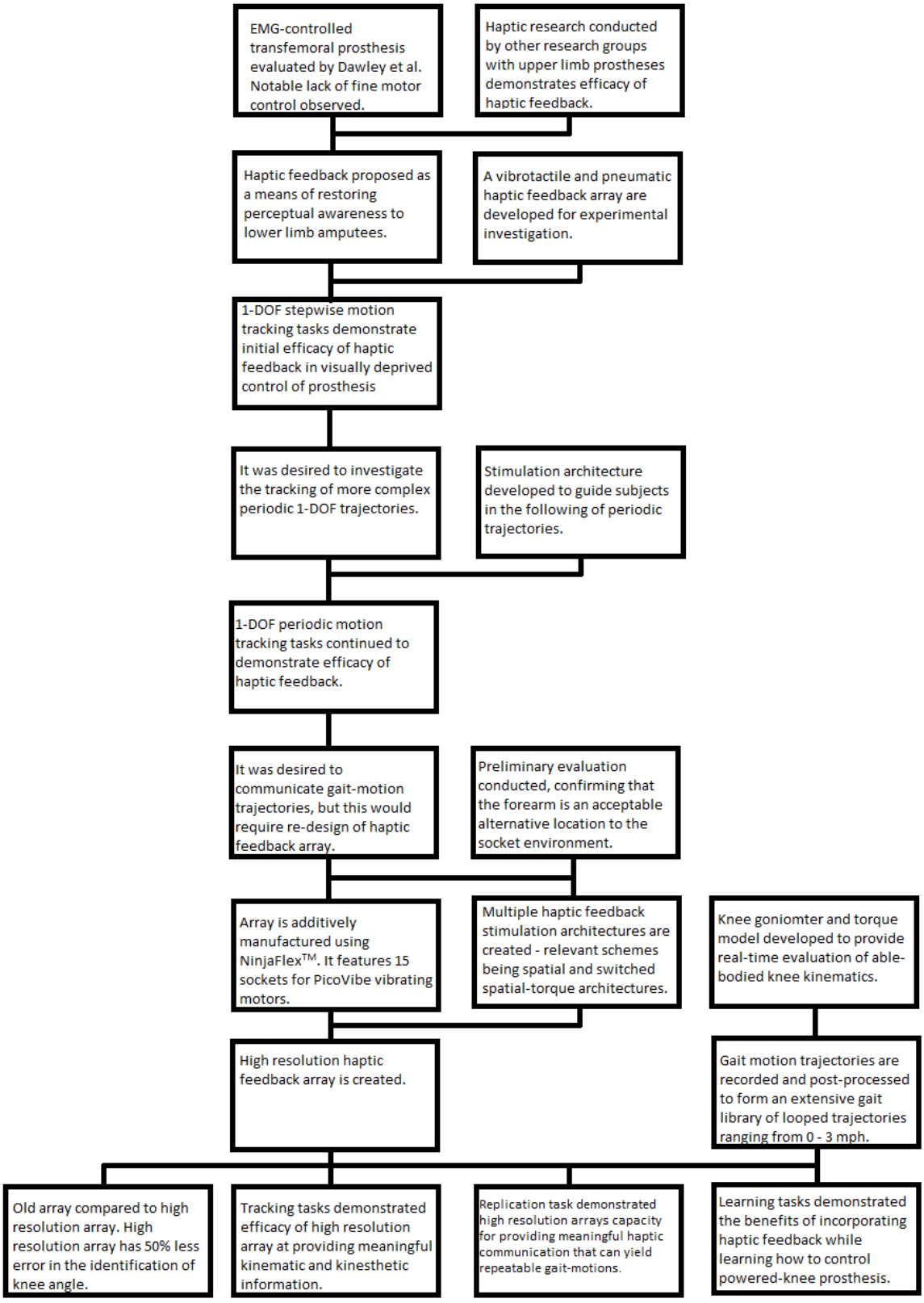

Figure 60: Flow chart of all work presented.

B. Contributions

i. Experimental validation of haptic feedback's capacity for providing corrective feedback in the volitional control of a powered transfemoral prosthesis.

ii. Design, development, and refinement of a novel haptic feedback array and communication methodology.

iii. Experimental validation of the high resolution haptic feedback array's capacity to communicate both desired motion trajectories as well as current limb-state information.

iv. Experimental validation of a high resolution haptic feedback array in providing an enhanced controls learning experience with an EMG-controlled powered knee prosthesis.

v. Demonstrate the efficacy of haptic presentation of knee kinematics/kinesthetic via the forearm.

IX. Future Works

While the works presented herein have established the efficacy of the high resolution haptic feedback array, it is important that its usage in prosthetic limb applications be better understood. Current research efforts are underway that are aimed at investigating how the haptic feedback array affects performance of the EMG-controlled transfemoral powered-knee prosthesis in amputee test subjects. While investigations are currently limited to one amputee test subject, the project will continue to expand and enroll new subjects as the current high resolution haptic feedback device transitions from an investigatory device into a market-ready product.

The initial aim of this work was to investigate the interactions of haptic feedback, lower limb perception, and powered transfemoral prosthesis control, but this device could have broader clinical impacts in other fields of medicine and rehabilitation. Looking at this device as a marketable product, it becomes important to consider how to best maximize its market share by understanding its breadth of application. While applications like stroke and spinal cord injury rehabilitation immediately come to mind, one should also remember the psychophysical effects that were observed with the haptic feedback device. With recent demonstrations of haptic feedback's ability to relieve parkinsonisms, the question then becomes – how else could this haptic feedback array be utilized as a rehabilitation tool (Rabin, 2013)? When considering these psychophysical phenomenon, the clinical capabilities of haptic feedback begin to broaden greatly. Further exploring the psychophysical effects of haptic feedback could offer unique solutions to proprioceptive

and neuropathic disorders like phantom limb pain, psychogenic disorders like functional tremors, or even more complex nervous system disorders like Tourette syndrome (Cole, 2009; Prochazka, 1996; Houghton, 2014). It is then proposed that these possible applications be investigated further through cooperation with local hospitals and rehabilitation centers. This can be done while the device undergoes the patenting process and proper FDA approval for further clinical evaluation.

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XI. Appendices

A. Statistical Analyses

1. Sinusoidal Motion Tracking

Descriptives

Frequency_Error

				95% Confidence Interval for Mean		Between-Component Variance
		Std. Deviation	Std. Error	Lower Bound	Upper Bound	
Model	Fixed Effects	.176935	.027302	.75769	.86854	
	Random Effects		.075869	.62747	.99876	.035075

Test of Homogeneity of Variances

Frequency_Error

Levene Statistic	df1	df2	Sig.
8.198	6	35	.000

ANOVA

Frequency_Error

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.451	6	.242	7.722	.000
Within Groups	1.096	35	.031		
Total	2.546	41			

Multiple Comparisons

Dependent Variable: Frequency_Error

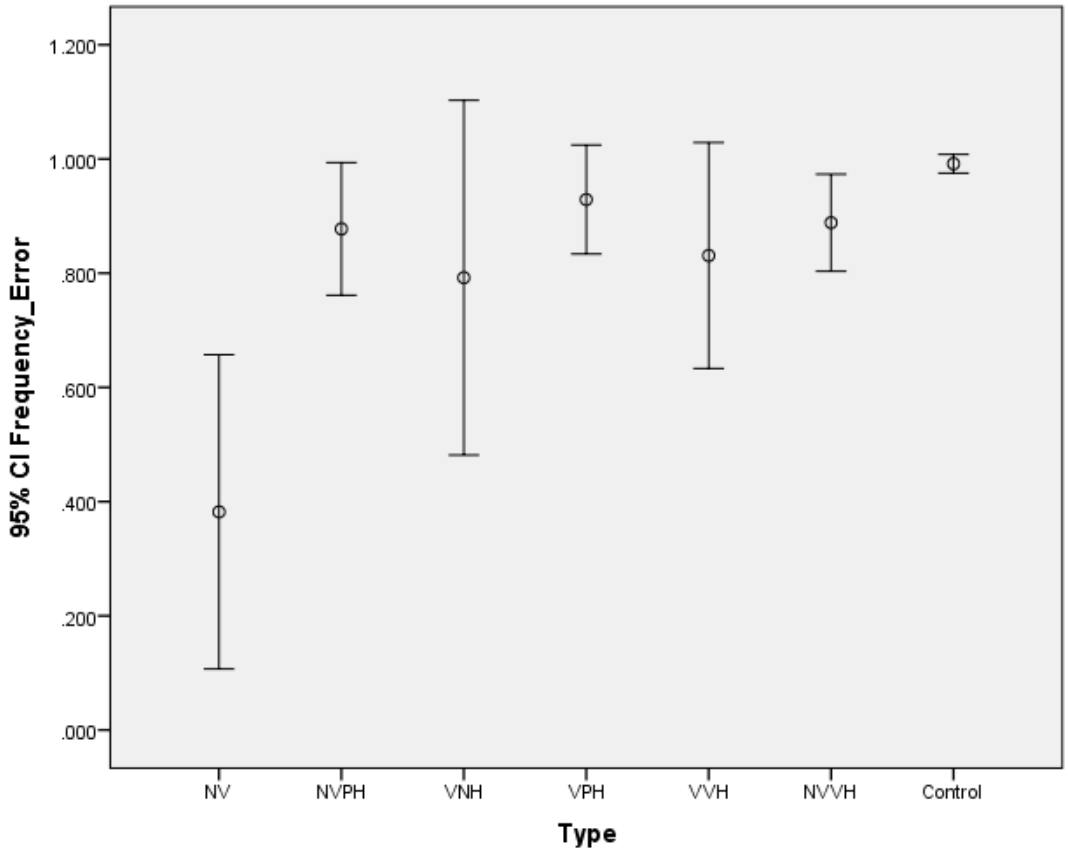
Tukey HSD

(I) Type	(J) Type	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
NV	NVPH	-.495500*	.102154	.000	-.81483	-.17617

	VNH	-.410167*	.102154	.005	-.72949	-.09084
	VPH	-.547000*	.102154	.000	-.86633	-.22767
	VVH	-.449000*	.102154	.002	-.76833	-.12967
	NVVH	-.506500*	.102154	.000	-.82583	-.18717
	Control	-.609667*	.102154	.000	-.92899	-.29034
NVPH	NV	.495500*	.102154	.000	.17617	.81483
	VNH	.085333	.102154	.979	-.23399	.40466
	VPH	-.051500	.102154	.999	-.37083	.26783
	VVH	.046500	.102154	.999	-.27283	.36583
	NVVH	-.011000	.102154	1.000	-.33033	.30833
	Control	-.114167	.102154	.918	-.43349	.20516
VNH	NV	.410167*	.102154	.005	.09084	.72949
	NVPH	-.085333	.102154	.979	-.40466	.23399
	VPH	-.136833	.102154	.829	-.45616	.18249
	VVH	-.038833	.102154	1.000	-.35816	.28049
	NVVH	-.096333	.102154	.963	-.41566	.22299
	Control	-.199500	.102154	.461	-.51883	.11983
VPH	NV	.547000*	.102154	.000	.22767	.86633
	NVPH	.051500	.102154	.999	-.26783	.37083
	VNH	.136833	.102154	.829	-.18249	.45616
	VVH	.098000	.102154	.959	-.22133	.41733
	NVVH	.040500	.102154	1.000	-.27883	.35983
	Control	-.062667	.102154	.996	-.38199	.25666
VVH	NV	.449000*	.102154	.002	.12967	.76833
	NVPH	-.046500	.102154	.999	-.36583	.27283
	VNH	.038833	.102154	1.000	-.28049	.35816
	VPH	-.098000	.102154	.959	-.41733	.22133
	NVVH	-.057500	.102154	.997	-.37683	.26183
	Control	-.160667	.102154	.700	-.47999	.15866
NVVH	NV	.506500*	.102154	.000	.18717	.82583
	NVPH	.011000	.102154	1.000	-.30833	.33033
	VNH	.096333	.102154	.963	-.22299	.41566
	VPH	-.040500	.102154	1.000	-.35983	.27883
	VVH	.057500	.102154	.997	-.26183	.37683
	Control	-.103167	.102154	.948	-.42249	.21616
Control	NV	.609667*	.102154	.000	.29034	.92899
	NVPH	.114167	.102154	.918	-.20516	.43349

VNH	.199500	.102154	.461	-.11983	.51883
VPH	.062667	.102154	.996	-.25666	.38199
VVH	.160667	.102154	.700	-.15866	.47999
NVVH	.103167	.102154	.948	-.21616	.42249

*. The mean difference is significant at the 0.05 level.



2. Spatial Test

Test of Homogeneity of Variances

Data

Levene Statistic	df1	df2	Sig.
14.711	1	142	.000

ANOVA

Data

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1338.340	1	1338.340	17.215	.000
Within Groups	11039.653	142	77.744		
Total	12377.993	143			

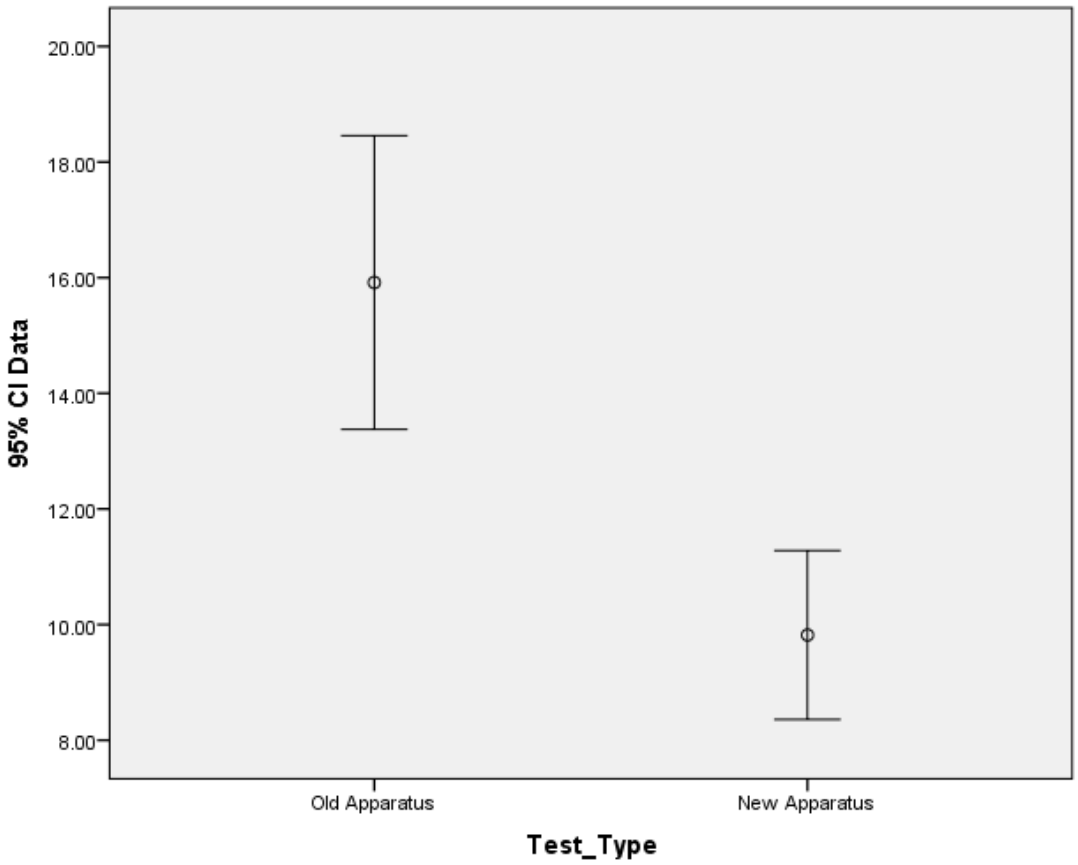
Robust Tests of Equality of Means

Data

	Statistic[a]	df1	df2	Sig.
Welch	17.215	1	113.316	.000
Brown-Forsythe	17.215	1	113.316	.000

a. Asymptotically F distributed.

Means Plots


20.00
18.00
16.00
14.00
12.00
10.00
8.00
95% CI Data
Old Apparatus
New Apparatus
Test_Type

3. Motion Tracking and Replication Analyses

ANOVA

TrakData

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1956.367	2	978.184	9.079	.000
Within Groups	21655.338	201	107.738		
Total	23611.706	203			

Robust Tests of Equality of Means

TrakData

	Statistic[a]	df1	df2	Sig.
Welch	13.074	2	92.629	.000
Brown-Forsythe	16.910	2	165.557	.000

a. Asymptotically F distributed.

Post Hoc Tests

Multiple Comparisons

Dependent Variable: TrakData

	(I) Tracking	(J) Tracking	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound
Tukey HSD	S_F_Tracking	C_F_Tracking	-.77778	2.4 4652	.9 46	- 6.5545
		Control	6.07323 *	1.9 5165	.0 06	1.4650
	C_F_Tracking	S_F_Tracking	.77778	2.4 4652	.9 46	- 4.9990
		Control	6.85101 *	1.9 5165	.0 02	2.2428
	Control	S_F_Tracking	- 6.07323*	1.9 5165	.0 06	- 10.6815
		C_F_Tracking	- 6.85101*	1.9 5165	.0 02	- 11.4592
LSD	S_F_Tracking	C_F_Tracking	-.77778	2.4 4652	.7 51	- 5.6019
		Control	6.07323 *	1.9 5165	.0 02	2.2249
	C_F_Tracking	S_F_Tracking	.77778	2.4 4652	.7 51	- 4.0464

		Control	6.85101*	1.95165	.001	3.0027
	Control	S_F_Tracking	-6.07323*	1.95165	.002	-9.9216
		C_F_Tracking	-6.85101*	1.95165	.001	-10.6993
Games-Howell	S_F_Tracking	C_F_Tracking	-.77778	1.47804	.859	-4.3185
		Control	6.07323*	1.52813	.000	2.4390
	C_F_Tracking	S_F_Tracking	.77778	1.47804	.859	-2.7629
		Control	6.85101*	1.42679	.000	3.4651
	Control	S_F_Tracking	-6.07323*	1.52813	.000	-9.7075
		C_F_Tracking	-6.85101*	1.42679	.000	-10.2370

Multiple Comparisons

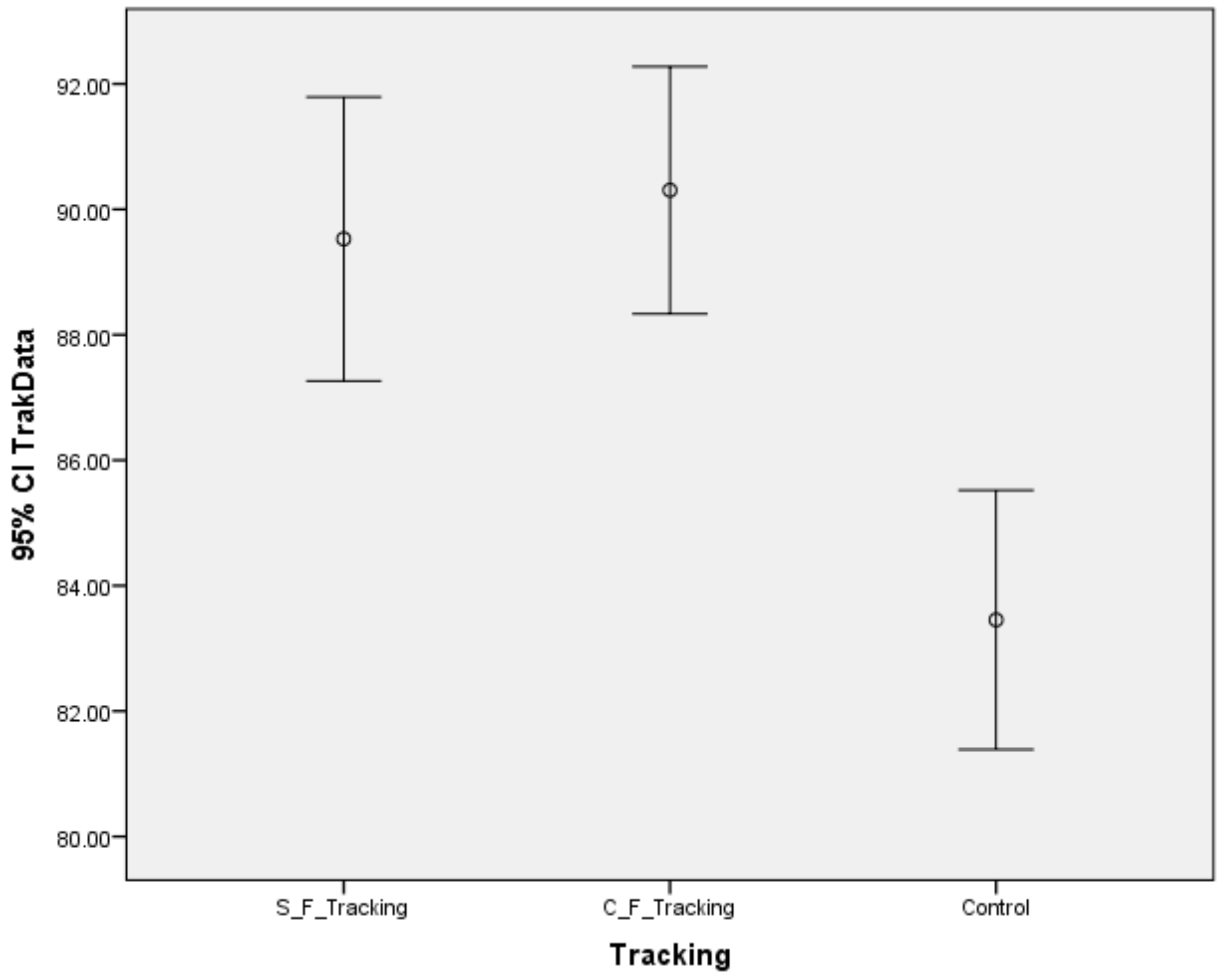
Dependent Variable: TrakData

			95% Confidence Interval
	(I) Tracking	(J) Tracking	Upper Bound
Tukey HSD	S_F_Tracking	C_F_Tracking	4.9990
		Control	10.6815
	C_F_Tracking	S_F_Tracking	6.5545
		Control	11.4592

	Control	S_F_Tracking	-1.4650
		C_F_Tracking	-2.2428
LSD	S_F_Tracking	C_F_Tracking	4.0464
		Control	9.9216
	C_F_Tracking	S_F_Tracking	5.6019
		Control	10.6993
	Control	S_F_Tracking	-2.2249
		C_F_Tracking	-3.0027
Games-Howell	S_F_Tracking	C_F_Tracking	2.7629
		Control	9.7075
	C_F_Tracking	S_F_Tracking	4.3185
		Control	10.2370
	Control	S_F_Tracking	-2.4390
		C_F_Tracking	-3.4651

*. The mean difference is significant at the 0.05 level.

Graph


95% CI TrakData
92.00
90.00
88.00
86.00
84.00
82.00
80.00
S_F_Tracking
C_F_Tracking
Control
Tracking

ANOVA

RepData

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2260.119	2	1130.059	9.455	.000
Within Groups	25458.506	213	119.524		
Total	27718.625	215			

Robust Tests of Equality of Means

RepData

	Statistic[a]	df1	df2	Sig.
Welch	12.525	2	61.910	.000
Brown-Forsythe	12.505	2	69.220	.000

a. Asymptotically F distributed.

Post Hoc Tests

Multiple Comparisons

Dependent Variable: RepData

	(I) Replication	(J) Replication	Mean Difference (I-J)	Std. Error	Sig.
Tukey HSD	S_F_Replication	C_F_Replication	1.53333	2.82281	.850
		Control	7.93205*	2.17952	.001
	C_F_Replication	S_F_Replication	-1.53333	2.82281	.850
		Control	6.39872*	2.17952	.010
	Control	S_F_Replication	-7.93205*	2.17952	.001
		C_F_Replication	-6.39872*	2.17952	.010
LSD	S_F_Replication	C_F_Replication	1.53333	2.82281	.588
		Control	7.93205*	2.17952	.000
	C_F_Replication	S_F_Replication	-1.53333	2.82281	.588
		Control	6.39872*	2.17952	.004
	Control	S_F_Replication	-7.93205*	2.17952	.000

		C_F_Replication	-6.39872*	2.17952	.004
Games-Howell	S_F_Replication	C_F_Replication	1.53333	2.35922	.793
		Control	7.93205*	2.27104	.003
	C_F_Replication	S_F_Replication	-1.53333	2.35922	.793
		Control	6.39872*	1.45379	.000
	Control	S_F_Replication	-7.93205*	2.27104	.003
		C_F_Replication	-6.39872*	1.45379	.000

Multiple Comparisons

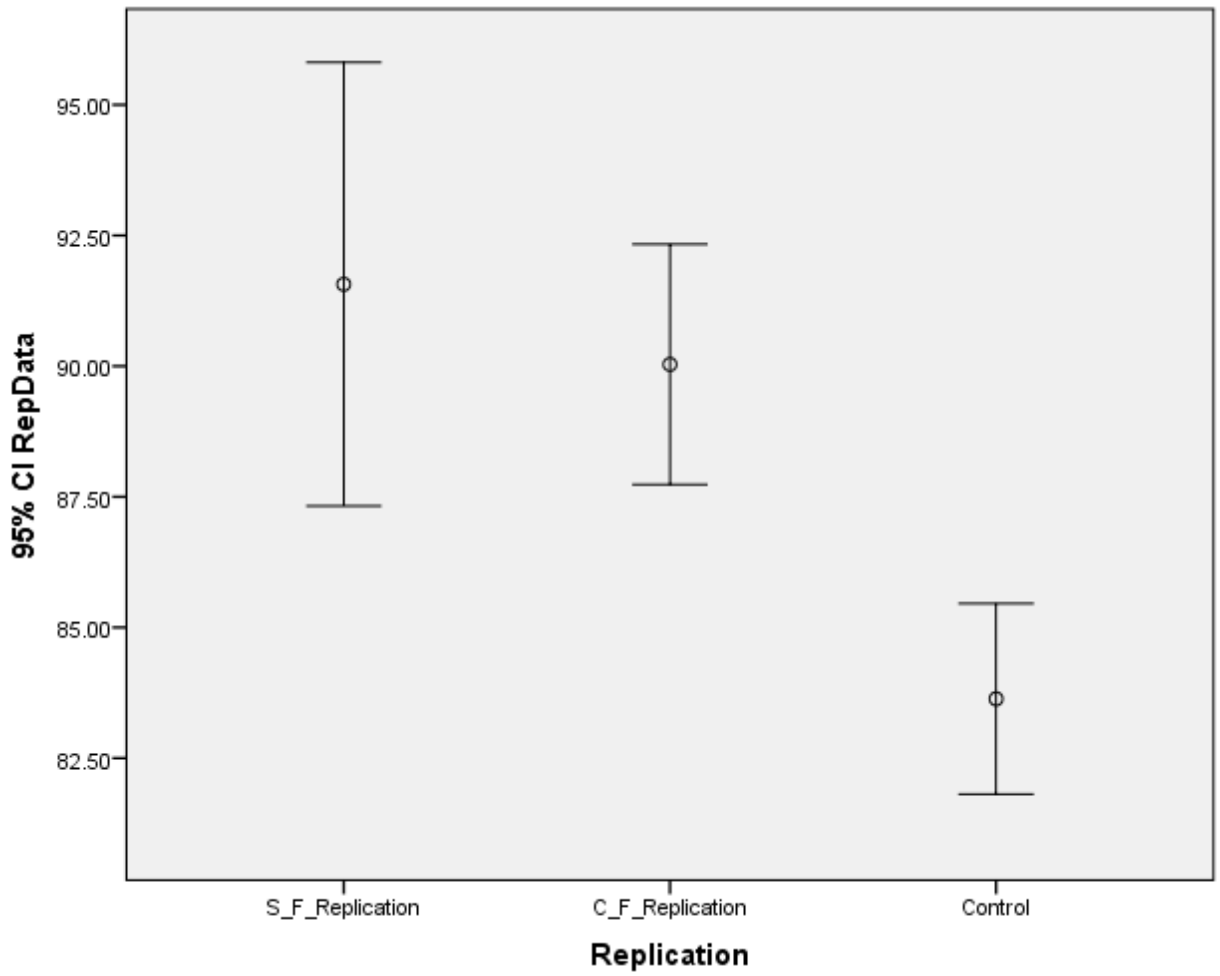
Dependent Variable: RepData

			95% Confidence Interval	
	(I) Replication	(J) Replication	Lower Bound	Upper Bound
Tukey HSD	S_F_Replication	C_F_Replication	-5.1291	8.1958
		Control	2.7879	13.0762
	C_F_Replication	S_F_Replication	-8.1958	5.1291
		Control	1.2546	11.5428
	Control	S_F_Replication	-13.0762	-2.7879
		C_F_Replication	-11.5428	-1.2546
LSD	S_F_Replication	C_F_Replication	-4.0309	7.0975
		Control	3.6359	12.2282

	C_F_Replication	S_F_Replication	-7.0975	4.0309
		Control	2.1025	10.6949
	Control	S_F_Replication	-12.2282	-3.6359
		C_F_Replication	-10.6949	-2.1025
Games-Howell	S_F_Replication	C_F_Replication	-4.1860	7.2527
		Control	2.4113	13.4528
	C_F_Replication	S_F_Replication	-7.2527	4.1860
		Control	2.9226	9.8748
	Control	S_F_Replication	-13.4528	-2.4113
		C_F_Replication	-9.8748	-2.9226

*. The mean difference is significant at the 0.05 level.

Graph


95% CI RepData
95.00
92.50
90.00
87.50
85.00
82.50
S_F_Replication
C_F_Replication
Control
Replication

ANOVA

CorrelationDat

		Sum of Squares	df	Mean Square	F	Sig.
Between Groups		487.037	3	162.346	.946	.421
Within Groups		21969.206	128	171.634		
Total		22456.242	131			

Robust Tests of Equality of Means

CorrelationDat

	Statistic[a]	df1	df2	Sig.
Welch	1.000	3	69.071	.398
Brown-Forsythe	.928	3	114.554	.430

a. Asymptotically F distributed.

Post Hoc Tests

Multiple Comparisons

Dependent Variable: CorrelationDat

	(I) Correlation	(J) Correlation	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	S_C_Tracking	C_C_Tracking	-.30556	3.08792	1.000	-8.3437	7.7326
		S_C_Replication	.23333	3.23864	1.000	-8.1972	8.6638
		C_C_Replication	-4.60000	3.23864	.489	-13.0305	3.8305
	C_C_Tracking	S_C_Tracking	.30556	3.08792	1.000	-7.7326	8.3437
		S_C_Replication	.53889	3.23864	.998	-7.8916	8.9694
		C_C_Replication	-4.29444	3.23864	.548	-12.7249	4.1361
	S_C_Replication	S_C_Tracking	-.23333	3.23864	1.000	-8.6638	8.1972
		C_C_Tracking	-.53889	3.23864	.998	-8.9694	7.8916
		C_C_Replication	-4.83333	3.38265	.484	-13.6387	3.9720

	C_C_Replication	S_C_Tracking	4.60000	3	.23864	.489	-3.83305	13.03305
		C_C_Tracking	4.29444	3	.23864	.548	-4.13619	12.72249
		S_C_Replication	4.83333	3	.38265	.484	-3.97203	13.63887
LSD	S_C_Tracking	C_C_Tracking	-.30556	3	.08792	.921	-6.41554	5.80044
		S_C_Replication	.23333	3	.23864	.943	-6.17491	6.64015
		C_C_Replication	-4.60000	3	.23864	.158	-11.00828	1.80828
	C_C_Tracking	S_C_Tracking	.30556	3	.08792	.921	-5.80443	6.41555
		S_C_Replication	.53889	3	.23864	.868	-5.86937	6.94715
		C_C_Replication	-4.29444	3	.23864	.187	-10.70263	2.11538
	S_C_Replication	S_C_Tracking	-.23333	3	.23864	.943	-6.64154	6.17549
		C_C_Tracking	-.53889	3	.23864	.868	-6.94715	5.86937
		C_C_Replication	-4.83333	3	.38265	.155	-11.52659	1.85998
	C_C_Replication	S_C_Tracking	4.60000	3	.23864	.158	-1.80828	11.00828
		C_C_Tracking	4.29444	3	.23864	.187	-2.11538	10.70263
		S_C_Replication	4.83333	3	.38265	.155	-1.85998	11.52659

Games-Howell	S_C_Tracking	C_C_Tracking	-.30556	2 .86698	1 .000	-7.8514	7.2402
		S_C_Replication	.23333	3 .48486	1 .000	-9.0088	9.4755
		C_C_Replication	-4.60000	3 .00772	. 427	-12.5448	3.3448
	C_C_Tracking	S_C_Tracking	.30556	2 .86698	1 .000	-7.2402	7.8514
		S_C_Replication	.53889	3 .53850	. 999	-8.8368	9.9145
		C_C_Replication	-4.29444	3 .06970	. 505	-12.3990	3.8101
	S_C_Replication	S_C_Tracking	-.23333	3 .48486	1 .000	-9.4755	9.0088
		C_C_Tracking	-.53889	3 .53850	. 999	-9.9145	8.8368
		C_C_Replication	-4.83333	3 .65346	. 553	-14.5125	4.8458
	C_C_Replication	S_C_Tracking	4.60000	3 .00772	. 427	-3.3448	12.5448
		C_C_Tracking	4.29444	3 .06970	. 505	-3.8101	12.3990
		S_C_Replication	4.83333	3 .65346	. 553	-4.8458	14.5125

Homogeneous Subsets

CorrelationDat

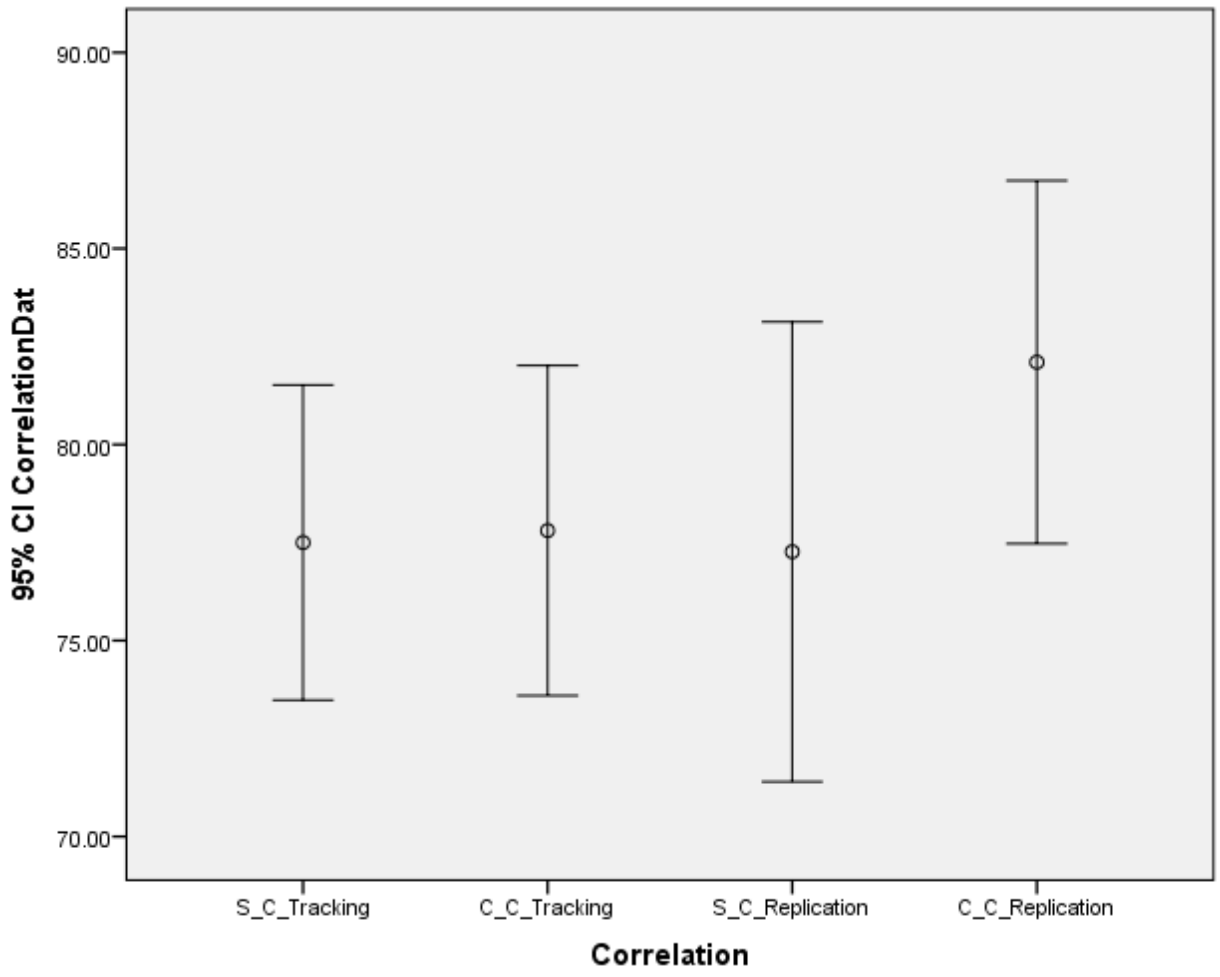
	Correlation	N	Subset for alpha = 0.05 1
Tukey HSD[a,b]	S_C_Replication	36	77.2667
	S_C_Tracking	36	77.5000
	C_C_Tracking	36	77.8056
	C_C_Replication	36	82.1000
	Sig.		.445

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 32.727.

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Graph


90.00
85.00
80.00
75.00
70.00
95% CI CorrelationDat
S_C_Tracking
C_C_Tracking
S_C_Replication
C_C_Replication
Correlation

4. Prosthetic Limb Gait-Motion Learning Analyses

Test of Homogeneity of Variances

Co_Dat

Levene Statistic	df1	df2	Sig.
2.020	9	50	.056

ANOVA

Co_Dat

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	18964.160	9	2107.129	9.444	.000
Within Groups	11156.208	50	223.124		
Total	30120.368	59			

Robust Tests of Equality of Means

Co_Dat

	Statistic[a]	df1	df2	Sig.
Welch	11.787	9	20.146	.000
Brown-Forsythe	9.444	9	21.393	.000

a. Asymptotically F distributed.

Post Hoc Tests

Multiple Comparisons

Dependent Variable: Co_Dat

	(I) Coherence	(J) Coherence	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	Lesson 1 Visual	Lesson 1 Haptic	-47.66667*	8.62408	.000	-76.2147	-19.1186
		Lesson 2 Visual	-32.95000*	8.62408	.012	-61.4980	-4.4020
		Lesson 2 Haptic	-54.50000*	8.62408	.000	-83.0480	-25.9520
		Lesson 3 Visual	-42.33333*	8.62408	.000	-70.8814	-13.7853
		Lesson 3 Haptic	-58.00000*	8.62408	.000	-86.5480	-29.4520
		Lesson 4 Visual	-55.50000*	8.62408	.000	-84.0480	-26.9520
		Lesson 4 Haptic	-66.83333*	8.62408	.000	-95.3814	-38.2853
		Lesson 5 Visual	-46.66667*	8.62408	.000	-75.2147	-18.1186
		Lesson 5 Haptic	-56.83333*	8.62408	.000	-85.3814	-28.2853
	Lesson 1 Haptic	Lesson 1 Visual	47.66667*	8.62408	.000	19.1186	76.2147
		Lesson 2 Visual	14.71667	8.62408	.787	-13.8314	43.2647

		Lesson 2 Haptic	-6.83333	8.62408	.998	-35.3814	21.7147
		Lesson 3 Visual	5.33333	8.62408	1.000	-23.2147	33.8814
		Lesson 3 Haptic	-10.33333	8.62408	.969	-38.8814	18.2147
		Lesson 4 Visual	-7.83333	8.62408	.995	-36.3814	20.7147
		Lesson 4 Haptic	-19.16667	8.62408	.456	-47.7147	9.3814
		Lesson 5 Visual	1.00000	8.62408	1.000	-27.5480	29.5480
		Lesson 5 Haptic	-9.16667	8.62408	.986	-37.7147	19.3814
	Lesson 2 Visual	Lesson 1 Visual	32.95000*	8.62408	.012	4.4020	61.4980
		Lesson 1 Haptic	-14.71667	8.62408	.787	-43.2647	13.8314
		Lesson 2 Haptic	-21.55000	8.62408	.294	-50.0980	6.9980
		Lesson 3 Visual	-9.38333	8.62408	.984	-37.9314	19.1647
		Lesson 3 Haptic	-25.05000	8.62408	.131	-53.5980	3.4980
		Lesson 4 Visual	-22.55000	8.62408	.238	-51.0980	5.9980
		Lesson 4 Haptic	-33.88333*	8.62408	.009	-62.4314	-5.3353
		Lesson 5 Visual	-13.71667	8.62408	.846	-42.2647	14.8314

		Lesson 5 Haptic	-23.88333	8.62408	.175	-52.4314	4.6647
	Lesson 2 Haptic	Lesson 1 Visual	54.50000*	8.62408	.000	25.9520	83.0480
		Lesson 1 Haptic	6.83333	8.62408	.998	-21.7147	35.3814
		Lesson 2 Visual	21.55000	8.62408	.294	-6.9980	50.0980
		Lesson 3 Visual	12.16667	8.62408	.918	-16.3814	40.7147
		Lesson 3 Haptic	-3.50000	8.62408	1.000	-32.0480	25.0480
		Lesson 4 Visual	-1.00000	8.62408	1.000	-29.5480	27.5480
		Lesson 4 Haptic	-12.33333	8.62408	.912	-40.8814	16.2147
		Lesson 5 Visual	7.83333	8.62408	.995	-20.7147	36.3814
		Lesson 5 Haptic	-2.33333	8.62408	1.000	-30.8814	26.2147
	Lesson 3 Visual	Lesson 1 Visual	42.33333*	8.62408	.000	13.7853	70.8814
		Lesson 1 Haptic	-5.33333	8.62408	1.000	-33.8814	23.2147
		Lesson 2 Visual	9.38333	8.62408	.984	-19.1647	37.9314
		Lesson 2 Haptic	-12.16667	8.62408	.918	-40.7147	16.3814
		Lesson 3 Haptic	-15.66667	8.62408	.722	-44.2147	12.8814

		Lesson 4 Visual	-13.16667	8.62408	.875	-41.7147	15.3814
		Lesson 4 Haptic	-24.50000	8.62408	.151	-53.0480	4.0480
		Lesson 5 Visual	-4.33333	8.62408	1.000	-32.8814	24.2147
		Lesson 5 Haptic	-14.50000	8.62408	.800	-43.0480	14.0480
	Lesson 3 Haptic	Lesson 1 Visual	58.00000*	8.62408	.000	29.4520	86.5480
		Lesson 1 Haptic	10.33333	8.62408	.969	-18.2147	38.8814
		Lesson 2 Visual	25.05000	8.62408	.131	-3.4980	53.5980
		Lesson 2 Haptic	3.50000	8.62408	1.000	-25.0480	32.0480
		Lesson 3 Visual	15.66667	8.62408	.722	-12.8814	44.2147
		Lesson 4 Visual	2.50000	8.62408	1.000	-26.0480	31.0480
		Lesson 4 Haptic	-8.83333	8.62408	.989	-37.3814	19.7147
		Lesson 5 Visual	11.33333	8.62408	.946	-17.2147	39.8814
		Lesson 5 Haptic	1.16667	8.62408	1.000	-27.3814	29.7147
	Lesson 4 Visual	Lesson 1 Visual	55.50000*	8.62408	.000	26.9520	84.0480
		Lesson 1 Haptic	7.83333	8.62408	.995	-20.7147	36.3814

		Lesson 2 Visual	22.55000	8.62408	.238	-5.9980	51.0980
		Lesson 2 Haptic	1.00000	8.62408	1.000	-27.5480	29.5480
		Lesson 3 Visual	13.16667	8.62408	.875	-15.3814	41.7147
		Lesson 3 Haptic	-2.50000	8.62408	1.000	-31.0480	26.0480
		Lesson 4 Haptic	-11.33333	8.62408	.946	-39.8814	17.2147
		Lesson 5 Visual	8.83333	8.62408	.989	-19.7147	37.3814
		Lesson 5 Haptic	-1.33333	8.62408	1.000	-29.8814	27.2147
	Lesson 4 Haptic	Lesson 1 Visual	66.83333*	8.62408	.000	38.2853	95.3814
		Lesson 1 Haptic	19.16667	8.62408	.456	-9.3814	47.7147
		Lesson 2 Visual	33.88333*	8.62408	.009	5.3353	62.4314
		Lesson 2 Haptic	12.33333	8.62408	.912	-16.2147	40.8814
		Lesson 3 Visual	24.50000	8.62408	.151	-4.0480	53.0480
		Lesson 3 Haptic	8.83333	8.62408	.989	-19.7147	37.3814
		Lesson 4 Visual	11.33333	8.62408	.946	-17.2147	39.8814
		Lesson 5 Visual	20.16667	8.62408	.384	-8.3814	48.7147

		Lesson 5 Haptic	10.00000	8.62408	.975	-18.5480	38.5480
	Lesson 5 Visual	Lesson 1 Visual	46.66667*	8.62408	.000	18.1186	75.2147
		Lesson 1 Haptic	-1.00000	8.62408	1.000	-29.5480	27.5480
		Lesson 2 Visual	13.71667	8.62408	.846	-14.8314	42.2647
		Lesson 2 Haptic	-7.83333	8.62408	.995	-36.3814	20.7147
		Lesson 3 Visual	4.33333	8.62408	1.000	-24.2147	32.8814
		Lesson 3 Haptic	-11.33333	8.62408	.946	-39.8814	17.2147
		Lesson 4 Visual	-8.83333	8.62408	.989	-37.3814	19.7147
		Lesson 4 Haptic	-20.16667	8.62408	.384	-48.7147	8.3814
		Lesson 5 Haptic	-10.16667	8.62408	.972	-38.7147	18.3814
	Lesson 5 Haptic	Lesson 1 Visual	56.83333*	8.62408	.000	28.2853	85.3814
		Lesson 1 Haptic	9.16667	8.62408	.986	-19.3814	37.7147
		Lesson 2 Visual	23.88333	8.62408	.175	-4.6647	52.4314
		Lesson 2 Haptic	2.33333	8.62408	1.000	-26.2147	30.8814
		Lesson 3 Visual	14.50000	8.62408	.800	-14.0480	43.0480

		Lesson 3 Haptic	-1.16667	8.62408	1.000	-29.7147	27.3814
		Lesson 4 Visual	1.33333	8.62408	1.000	-27.2147	29.8814
		Lesson 4 Haptic	-10.00000	8.62408	.975	-38.5480	18.5480
		Lesson 5 Visual	10.16667	8.62408	.972	-18.3814	38.7147
Games-Howell	Lesson 1 Visual	Lesson 1 Haptic	-47.66667	13.27738	.109	-103.9172	8.5839
		Lesson 2 Visual	-32.95000	11.78635	.269	-81.5854	15.6854
		Lesson 2 Haptic	-54.50000*	8.36693	.002	-87.7406	-21.2594
		Lesson 3 Visual	-42.33333*	8.35331	.011	-75.5268	-9.1399
		Lesson 3 Haptic	-58.00000*	6.76429	.001	-88.0884	-27.9116
		Lesson 4 Visual	-55.50000*	7.02891	.001	-85.6171	-25.3829
		Lesson 4 Haptic	-66.83333*	6.54939	.001	-97.1558	-36.5108
		Lesson 5 Visual	-46.66667*	7.09147	.004	-76.8318	-16.5016
		Lesson 5 Haptic	-56.83333*	6.64036	.002	-87.0239	-26.6428
	Lesson 1 Haptic	Lesson 1 Visual	47.66667	13.27738	.109	-8.5839	103.9172
		Lesson 2 Visual	14.71667	15.37264	.989	-46.4776	75.9110

		Lesson 2 Haptic	-6.83333	12.93853	1.000	-62.8534	49.1867
		Lesson 3 Visual	5.33333	12.92972	1.000	-50.6839	61.3506
		Lesson 3 Haptic	-10.33333	11.96476	.992	-67.3232	46.6565
		Lesson 4 Visual	-7.83333	12.11633	.999	-64.4683	48.8016
		Lesson 4 Haptic	-19.16667	11.84460	.803	-76.5067	38.1733
		Lesson 5 Visual	1.00000	12.15273	1.000	-55.5630	57.5630
		Lesson 5 Haptic	-9.16667	11.89514	.996	-66.3516	48.0182
	Lesson 2 Visual	Lesson 1 Visual	32.95000	11.78635	.269	-15.6854	81.5854
		Lesson 1 Haptic	-14.71667	15.37264	.989	-75.9110	46.4776
		Lesson 2 Haptic	-21.55000	11.40328	.677	-69.5994	26.4994
		Lesson 3 Visual	-9.38333	11.39329	.995	-57.4211	38.6544
		Lesson 3 Haptic	-25.05000	10.28517	.437	-73.4332	23.3332
		Lesson 4 Visual	-22.55000	10.46111	.553	-70.6056	25.5056
		Lesson 4 Haptic	-33.88333	10.14513	.190	-82.6285	14.8618
		Lesson 5 Visual	-13.71667	10.50324	.920	-61.7128	34.2795

		Lesson 5 Haptic	-23.88333	10.20410	.477	-72.4643	24.6976
	Lesson 2 Haptic	Lesson 1 Visual	54.50000*	8.36693	.002	21.2594	87.7406
		Lesson 1 Haptic	6.83333	12.93853	1.000	-49.1867	62.8534
		Lesson 2 Visual	21.55000	11.40328	.677	-26.4994	69.5994
		Lesson 3 Visual	12.16667	7.80349	.841	-18.7248	43.0581
		Lesson 3 Haptic	-3.50000	6.07225	1.000	-29.9639	22.9639
		Lesson 4 Visual	-1.00000	6.36571	1.000	-27.6895	25.6895
		Lesson 4 Haptic	-12.33333	5.83190	.571	-38.9236	14.2569
		Lesson 5 Visual	7.83333	6.43471	.949	-18.9562	34.6229
		Lesson 5 Haptic	-2.33333	5.93390	1.000	-28.8289	24.1622
	Lesson 3 Visual	Lesson 1 Visual	42.33333*	8.35331	.011	9.1399	75.5268
		Lesson 1 Haptic	-5.33333	12.92972	1.000	-61.3506	50.6839
		Lesson 2 Visual	9.38333	11.39329	.995	-38.6544	57.4211
		Lesson 2 Haptic	-12.16667	7.80349	.841	-43.0581	18.7248
		Lesson 3 Haptic	-15.66667	6.05347	.359	-42.0323	10.6990

		Lesson 4 Visual	-13.16667	6.34779	.582	-39.7644	13.4311
		Lesson 4 Haptic	-24.50000	5.81234	.070	-50.9882	1.9882
		Lesson 5 Visual	-4.33333	6.41699	.999	-31.0328	22.3661
		Lesson 5 Haptic	-14.50000	5.91467	.418	-40.8949	11.8949
	Lesson 3 Haptic	Lesson 1 Visual	58.00000*	6.76429	.001	27.9116	88.0884
		Lesson 1 Haptic	10.33333	11.96476	.992	-46.6565	67.3232
		Lesson 2 Visual	25.05000	10.28517	.437	-23.3332	73.4332
		Lesson 2 Haptic	3.50000	6.07225	1.000	-22.9639	29.9639
		Lesson 3 Visual	15.66667	6.05347	.359	-10.6990	42.0323
		Lesson 4 Visual	2.50000	4.03388	1.000	-13.6484	18.6484
		Lesson 4 Haptic	-8.83333	3.12428	.251	-21.4398	3.7731
		Lesson 5 Visual	11.33333	4.14193	.279	-5.3196	27.9863
		Lesson 5 Haptic	1.16667	3.31076	1.000	-12.0066	14.3399
	Lesson 4 Visual	Lesson 1 Visual	55.50000*	7.02891	.001	25.3829	85.6171
		Lesson 1 Haptic	7.83333	12.11633	.999	-48.8016	64.4683

		Lesson 2 Visual	22.55000	10.46111	.553	-25.5056	70.6056
		Lesson 2 Haptic	1.00000	6.36571	1.000	-25.6895	27.6895
		Lesson 3 Visual	13.16667	6.34779	.582	-13.4311	39.7644
		Lesson 3 Haptic	-2.50000	4.03388	1.000	-18.6484	13.6484
		Lesson 4 Haptic	-11.33333	3.66212	.191	-26.6102	3.9435
		Lesson 5 Visual	8.83333	4.56131	.651	-9.2306	26.8972
		Lesson 5 Haptic	-1.33333	3.82245	1.000	-16.9161	14.2495
	Lesson 4 Haptic	Lesson 1 Visual	66.83333*	6.54939	.001	36.5108	97.1558
		Lesson 1 Haptic	19.16667	11.84460	.803	-38.1733	76.5067
		Lesson 2 Visual	33.88333	10.14513	.190	-14.8618	82.6285
		Lesson 2 Haptic	12.33333	5.83190	.571	-14.2569	38.9236
		Lesson 3 Visual	24.50000	5.81234	.070	-1.9882	50.9882
		Lesson 3 Haptic	8.83333	3.12428	.251	-3.7731	21.4398
		Lesson 4 Visual	11.33333	3.66212	.191	-3.9435	26.6102
		Lesson 5 Visual	20.16667*	3.78080	.013	4.2826	36.0507

		Lesson 5 Haptic	10.00000	2.84605	.096	-1.3216	21.3216
	Lesson 5 Visual	Lesson 1 Visual	46.66667*	7.09147	.004	16.5016	76.8318
		Lesson 1 Haptic	-1.00000	12.15273	1.000	-57.5630	55.5630
		Lesson 2 Visual	13.71667	10.50324	.920	-34.2795	61.7128
		Lesson 2 Haptic	-7.83333	6.43471	.949	-34.6229	18.9562
		Lesson 3 Visual	4.33333	6.41699	.999	-22.3661	31.0328
		Lesson 3 Haptic	-11.33333	4.14193	.279	-27.9863	5.3196
		Lesson 4 Visual	-8.83333	4.56131	.651	-26.8972	9.2306
		Lesson 4 Haptic	-20.16667*	3.78080	.013	-36.0507	-4.2826
		Lesson 5 Haptic	-10.16667	3.93630	.343	-26.3127	5.9793
	Lesson 5 Haptic	Lesson 1 Visual	56.83333*	6.64036	.002	26.6428	87.0239
		Lesson 1 Haptic	9.16667	11.89514	.996	-48.0182	66.3516
		Lesson 2 Visual	23.88333	10.20410	.477	-24.6976	72.4643
		Lesson 2 Haptic	2.33333	5.93390	1.000	-24.1622	28.8289
		Lesson 3 Visual	14.50000	5.91467	.418	-11.8949	40.8949

	Lesson 3 Haptic	-1.16667	3.31076	1.000	-14.3399	12.0066
	Lesson 4 Visual	1.33333	3.82245	1.000	-14.2495	16.9161
	Lesson 4 Haptic	-10.00000	2.84605	.096	-21.3216	1.3216
	Lesson 5 Visual	10.16667	3.93630	.343	-5.9793	26.3127

*. The mean difference is significant at the 0.05 level.

Homogeneous Subsets

Co_Dat

			Subset for alpha = 0.05		
	Coherence	N	1	2	3
Tukey HSD[a]	Lesson 1 Visual	6	18.6667		
	Lesson 2 Visual	6		51.6167	
	Lesson 3 Visual	6		61.0000	61.0000
	Lesson 5 Visual	6		65.3333	65.3333
	Lesson 1 Haptic	6		66.3333	66.3333
	Lesson 2 Haptic	6		73.1667	73.1667
	Lesson 4 Visual	6		74.1667	74.1667
	Lesson 5 Haptic	6		75.5000	75.5000
	Lesson 3 Haptic	6		76.6667	76.6667

	Lesson 4 Haptic	6			85.5000
	Sig.		1.000	.131	.151

Means for groups in homogeneous subsets are displayed.

Test of Homogeneity of Variances

Step_Dat

Levene Statistic	df1	df2	Sig.
3.796	9	50	.001

ANOVA

Step_Dat

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	12977.483	9	1441.943	7.377	.000
Within Groups	9773.500	50	195.470		
Total	22750.983	59			

Robust Tests of Equality of Means

Step_Dat

	Statistic[a]	df1	df2	Sig.
Welch	6.526	9	20.050	.000
Brown-Forsythe	7.377	9	24.230	.000

a. Asymptotically F distributed.

Post Hoc Tests

Multiple Comparisons

Dependent Variable: Step_Dat

	(I) Step_Length	(J) Step_Length	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Tukey HSD	Lesson 1 Visual	Lesson 1 Haptic	-35.33333*	8.07197	.002	-62.0537	-8.6129
		Lesson 2 Visual	3.33333	8.07197	1.000	-23.3871	30.0537
		Lesson 2 Haptic	-27.33333*	8.07197	.041	-54.0537	-.6129
		Lesson 3 Visual	-20.66667	8.07197	.263	-47.3871	6.0537
		Lesson 3 Haptic	-37.16667*	8.07197	.001	-63.8871	-10.4463
		Lesson 4 Visual	-16.33333	8.07197	.587	-43.0537	10.3871

	Lesson 4 Haptic	-33.66667*	8.07197	.004	-60.3871	-6.9463
	Lesson 5 Visual	-6.66667	8.07197	.998	-33.3871	20.0537
	Lesson 5 Haptic	-36.33333*	8.07197	.002	-63.0537	-9.6129
Lesson 1 Haptic	Lesson 1 Visual	35.33333*	8.07197	.002	8.6129	62.0537
	Lesson 2 Visual	38.66667*	8.07197	.001	11.9463	65.3871
	Lesson 2 Haptic	8.00000	8.07197	.992	-18.7204	34.7204
	Lesson 3 Visual	14.66667	8.07197	.722	-12.0537	41.3871
	Lesson 3 Haptic	-1.83333	8.07197	1.000	-28.5537	24.8871
	Lesson 4 Visual	19.00000	8.07197	.375	-7.7204	45.7204
	Lesson 4 Haptic	1.66667	8.07197	1.000	-25.0537	28.3871
	Lesson 5 Visual	28.66667*	8.07197	.026	1.9463	55.3871
	Lesson 5 Haptic	-1.00000	8.07197	1.000	-27.7204	25.7204
Lesson 2 Visual	Lesson 1 Visual	-3.33333	8.07197	1.000	-30.0537	23.3871
	Lesson 1 Haptic	-38.66667*	8.07197	.001	-65.3871	-11.9463
	Lesson 2 Haptic	-30.66667*	8.07197	.013	-57.3871	-3.9463

		Lesson 3 Visual	-24.00000	8.07197	.113	-50.7204	2.7204
		Lesson 3 Haptic	-40.50000*	8.07197	.000	-67.2204	-13.7796
		Lesson 4 Visual	-19.66667	8.07197	.327	-46.3871	7.0537
		Lesson 4 Haptic	-37.00000*	8.07197	.001	-63.7204	-10.2796
		Lesson 5 Visual	-10.00000	8.07197	.962	-36.7204	16.7204
		Lesson 5 Haptic	-39.66667*	8.07197	.000	-66.3871	-12.9463
	Lesson 2 Haptic	Lesson 1 Visual	27.33333*	8.07197	.041	.6129	54.0537
		Lesson 1 Haptic	-8.00000	8.07197	.992	-34.7204	18.7204
		Lesson 2 Visual	30.66667*	8.07197	.013	3.9463	57.3871
		Lesson 3 Visual	6.66667	8.07197	.998	-20.0537	33.3871
		Lesson 3 Haptic	-9.83333	8.07197	.966	-36.5537	16.8871
		Lesson 4 Visual	11.00000	8.07197	.933	-15.7204	37.7204
		Lesson 4 Haptic	-6.33333	8.07197	.999	-33.0537	20.3871
		Lesson 5 Visual	20.66667	8.07197	.263	-6.0537	47.3871
		Lesson 5 Haptic	-9.00000	8.07197	.981	-35.7204	17.7204

	Lesson 3 Visual	Lesson 1 Visual	20.66667	8.07197	.263	-6.0537	47.3871
		Lesson 1 Haptic	-14.66667	8.07197	.722	-41.3871	12.0537
		Lesson 2 Visual	24.00000	8.07197	.113	-2.7204	50.7204
		Lesson 2 Haptic	-6.66667	8.07197	.998	-33.3871	20.0537
		Lesson 3 Haptic	-16.50000	8.07197	.574	-43.2204	10.2204
		Lesson 4 Visual	4.33333	8.07197	1.000	-22.3871	31.0537
		Lesson 4 Haptic	-13.00000	8.07197	.837	-39.7204	13.7204
		Lesson 5 Visual	14.00000	8.07197	.771	-12.7204	40.7204
		Lesson 5 Haptic	-15.66667	8.07197	.642	-42.3871	11.0537
	Lesson 3 Haptic	Lesson 1 Visual	37.16667*	8.07197	.001	10.4463	63.8871
		Lesson 1 Haptic	1.83333	8.07197	1.000	-24.8871	28.5537
		Lesson 2 Visual	40.50000*	8.07197	.000	13.7796	67.2204
		Lesson 2 Haptic	9.83333	8.07197	.966	-16.8871	36.5537
		Lesson 3 Visual	16.50000	8.07197	.574	-10.2204	43.2204
		Lesson 4 Visual	20.83333	8.07197	.254	-5.8871	47.5537

		Lesson 4 Haptic	3.50000	8.07197	1.000	-23.2204	30.2204
		Lesson 5 Visual	30.50000*	8.07197	.014	3.7796	57.2204
		Lesson 5 Haptic	.83333	8.07197	1.000	-25.8871	27.5537
	Lesson 4 Visual	Lesson 1 Visual	16.33333	8.07197	.587	-10.3871	43.0537
		Lesson 1 Haptic	-19.00000	8.07197	.375	-45.7204	7.7204
		Lesson 2 Visual	19.66667	8.07197	.327	-7.0537	46.3871
		Lesson 2 Haptic	-11.00000	8.07197	.933	-37.7204	15.7204
		Lesson 3 Visual	-4.33333	8.07197	1.000	-31.0537	22.3871
		Lesson 3 Haptic	-20.83333	8.07197	.254	-47.5537	5.8871
		Lesson 4 Haptic	-17.33333	8.07197	.505	-44.0537	9.3871
		Lesson 5 Visual	9.66667	8.07197	.969	-17.0537	36.3871
		Lesson 5 Haptic	-20.00000	8.07197	.305	-46.7204	6.7204
	Lesson 4 Haptic	Lesson 1 Visual	33.66667*	8.07197	.004	6.9463	60.3871
		Lesson 1 Haptic	-1.66667	8.07197	1.000	-28.3871	25.0537
		Lesson 2 Visual	37.00000*	8.07197	.001	10.2796	63.7204

		Lesson 2 Haptic	6.33333	8.07197	.999	-20.3871	33.0537
		Lesson 3 Visual	13.00000	8.07197	.837	-13.7204	39.7204
		Lesson 3 Haptic	-3.50000	8.07197	1.000	-30.2204	23.2204
		Lesson 4 Visual	17.33333	8.07197	.505	-9.3871	44.0537
		Lesson 5 Visual	27.00000*	8.07197	.046	.2796	53.7204
		Lesson 5 Haptic	-2.66667	8.07197	1.000	-29.3871	24.0537
	Lesson 5 Visual	Lesson 1 Visual	6.66667	8.07197	.998	-20.0537	33.3871
		Lesson 1 Haptic	-28.66667*	8.07197	.026	-55.3871	-1.9463
		Lesson 2 Visual	10.00000	8.07197	.962	-16.7204	36.7204
		Lesson 2 Haptic	-20.66667	8.07197	.263	-47.3871	6.0537
		Lesson 3 Visual	-14.00000	8.07197	.771	-40.7204	12.7204
		Lesson 3 Haptic	-30.50000*	8.07197	.014	-57.2204	-3.7796
		Lesson 4 Visual	-9.66667	8.07197	.969	-36.3871	17.0537
		Lesson 4 Haptic	-27.00000*	8.07197	.046	-53.7204	-.2796
		Lesson 5 Haptic	-29.66667*	8.07197	.019	-56.3871	-2.9463

	Lesson 5 Haptic	Lesson 1 Visual	36.33333*	8.07197	.002	9.6129	63.0537
		Lesson 1 Haptic	1.00000	8.07197	1.000	-25.7204	27.7204
		Lesson 2 Visual	39.66667*	8.07197	.000	12.9463	66.3871
		Lesson 2 Haptic	9.00000	8.07197	.981	-17.7204	35.7204
		Lesson 3 Visual	15.66667	8.07197	.642	-11.0537	42.3871
		Lesson 3 Haptic	-.83333	8.07197	1.000	-27.5537	25.8871
		Lesson 4 Visual	20.00000	8.07197	.305	-6.7204	46.7204
		Lesson 4 Haptic	2.66667	8.07197	1.000	-24.0537	29.3871
		Lesson 5 Visual	29.66667*	8.07197	.019	2.9463	56.3871

Homogeneous Subsets

Step_Dat

	Step_Length	N	Subset for alpha = 0.05		
			1	2	3
Tukey HSD[a]	Lesson 2 Visual	6	54.8333		
	Lesson 1 Visual	6	58.1667		
	Lesson 5 Visual	6	64.8333	64.8333	
	Lesson 4 Visual	6	74.5000	74.5000	74.5000
	Lesson 3 Visual	6	78.8333	78.8333	78.8333
	Lesson 2 Haptic	6		85.5000	85.5000
	Lesson 4 Haptic	6			91.8333
	Lesson 1 Haptic	6			93.5000
	Lesson 5 Haptic	6			94.5000
	Lesson 3 Haptic	6			95.3333
	Sig.		.113	.263	.254

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 6.000.

Test of Homogeneity of Variances

Freq_Dat

Levene Statistic	df1	df2	Sig.
5.961	9	50	.000

ANOVA

Freq_Dat

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	16880.933	9	1875.659	14.073	.000
Within Groups	6664.000	50	133.280		
Total	23544.933	59			

Robust Tests of Equality of Means

Freq_Dat

	Statistic[a]	df1	df2	Sig.
Welch	27.689	9	19.754	.000
Brown-Forsythe	14.073	9	26.765	.000

a. Asymptotically F distributed.

Post Hoc Tests

Multiple Comparisons

Dependent Variable: Freq_Dat

	(I) Frequency	(J) Frequency	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	Lesson 1 Visual	Lesson 1 Haptic	-33.66667*	6.66533	.000	-55.7307	-11.6026
		Lesson 2 Visual	-1.50000	6.66533	1.000	-23.5641	20.5641
		Lesson 2 Haptic	-35.00000*	6.66533	.000	-57.0641	-12.9359
		Lesson 3 Visual	-14.00000	6.66533	.536	-36.0641	8.0641
		Lesson 3 Haptic	-36.50000*	6.66533	.000	-58.5641	-14.4359
		Lesson 4 Visual	-7.16667	6.66533	.985	-29.2307	14.8974
		Lesson 4 Haptic	-42.16667*	6.66533	.000	-64.2307	-20.1026
		Lesson 5 Visual	-14.33333	6.66533	.503	-36.3974	7.7307
		Lesson 5 Haptic	-47.66667*	6.66533	.000	-69.7307	-25.6026
	Lesson 1 Haptic	Lesson 1 Visual	33.66667*	6.66533	.000	11.6026	55.7307
		Lesson 2 Visual	32.16667*	6.66533	.001	10.1026	54.2307

		Lesson 2 Haptic	-1.33333	6.66533	1.000	-23.3974	20.7307
		Lesson 3 Visual	19.66667	6.66533	.119	-2.3974	41.7307
		Lesson 3 Haptic	-2.83333	6.66533	1.000	-24.8974	19.2307
		Lesson 4 Visual	26.50000*	6.66533	.008	4.4359	48.5641
		Lesson 4 Haptic	-8.50000	6.66533	.955	-30.5641	13.5641
		Lesson 5 Visual	19.33333	6.66533	.133	-2.7307	41.3974
		Lesson 5 Haptic	-14.00000	6.66533	.536	-36.0641	8.0641
	Lesson 2 Visual	Lesson 1 Visual	1.50000	6.66533	1.000	-20.5641	23.5641
		Lesson 1 Haptic	-32.16667*	6.66533	.001	-54.2307	-10.1026
		Lesson 2 Haptic	-33.50000*	6.66533	.000	-55.5641	-11.4359
		Lesson 3 Visual	-12.50000	6.66533	.685	-34.5641	9.5641
		Lesson 3 Haptic	-35.00000*	6.66533	.000	-57.0641	-12.9359
		Lesson 4 Visual	-5.66667	6.66533	.997	-27.7307	16.3974
		Lesson 4 Haptic	-40.66667*	6.66533	.000	-62.7307	-18.6026
		Lesson 5 Visual	-12.83333	6.66533	.652	-34.8974	9.2307

		Lesson 5 Haptic	-46.16667*	6.66533	.000	-68.2307	-24.1026
	Lesson 2 Haptic	Lesson 1 Visual	35.00000*	6.66533	.000	12.9359	57.0641
		Lesson 1 Haptic	1.33333	6.66533	1.000	-20.7307	23.3974
		Lesson 2 Visual	33.50000*	6.66533	.000	11.4359	55.5641
		Lesson 3 Visual	21.00000	6.66533	.074	-1.0641	43.0641
		Lesson 3 Haptic	-1.50000	6.66533	1.000	-23.5641	20.5641
		Lesson 4 Visual	27.83333*	6.66533	.004	5.7693	49.8974
		Lesson 4 Haptic	-7.16667	6.66533	.985	-29.2307	14.8974
		Lesson 5 Visual	20.66667	6.66533	.084	-1.3974	42.7307
		Lesson 5 Haptic	-12.66667	6.66533	.669	-34.7307	9.3974
	Lesson 3 Visual	Lesson 1 Visual	14.00000	6.66533	.536	-8.0641	36.0641
		Lesson 1 Haptic	-19.66667	6.66533	.119	-41.7307	2.3974
		Lesson 2 Visual	12.50000	6.66533	.685	-9.5641	34.5641
		Lesson 2 Haptic	-21.00000	6.66533	.074	-43.0641	1.0641
		Lesson 3 Haptic	-22.50000*	6.66533	.042	-44.5641	-.4359

		Lesson 4 Visual	6.83333	6.66533	.989	-15.2307	28.8974
		Lesson 4 Haptic	-28.16667*	6.66533	.004	-50.2307	-6.1026
		Lesson 5 Visual	-.33333	6.66533	1.000	-22.3974	21.7307
		Lesson 5 Haptic	-33.66667*	6.66533	.000	-55.7307	-11.6026
	Lesson 3 Haptic	Lesson 1 Visual	36.50000*	6.66533	.000	14.4359	58.5641
		Lesson 1 Haptic	2.83333	6.66533	1.000	-19.2307	24.8974
		Lesson 2 Visual	35.00000*	6.66533	.000	12.9359	57.0641
		Lesson 2 Haptic	1.50000	6.66533	1.000	-20.5641	23.5641
		Lesson 3 Visual	22.50000*	6.66533	.042	.4359	44.5641
		Lesson 4 Visual	29.33333*	6.66533	.002	7.2693	51.3974
		Lesson 4 Haptic	-5.66667	6.66533	.997	-27.7307	16.3974
		Lesson 5 Visual	22.16667*	6.66533	.048	.1026	44.2307
		Lesson 5 Haptic	-11.16667	6.66533	.804	-33.2307	10.8974
	Lesson 4 Visual	Lesson 1 Visual	7.16667	6.66533	.985	-14.8974	29.2307
		Lesson 1 Haptic	-26.50000*	6.66533	.008	-48.5641	-4.4359

		Lesson 2 Visual	5.66667	6.66533	.997	-16.3974	27.7307
		Lesson 2 Haptic	-27.83333*	6.66533	.004	-49.8974	-5.7693
		Lesson 3 Visual	-6.83333	6.66533	.989	-28.8974	15.2307
		Lesson 3 Haptic	-29.33333*	6.66533	.002	-51.3974	-7.2693
		Lesson 4 Haptic	-35.00000*	6.66533	.000	-57.0641	-12.9359
		Lesson 5 Visual	-7.16667	6.66533	.985	-29.2307	14.8974
		Lesson 5 Haptic	-40.50000*	6.66533	.000	-62.5641	-18.4359
	Lesson 4 Haptic	Lesson 1 Visual	42.16667*	6.66533	.000	20.1026	64.2307
		Lesson 1 Haptic	8.50000	6.66533	.955	-13.5641	30.5641
		Lesson 2 Visual	40.66667*	6.66533	.000	18.6026	62.7307
		Lesson 2 Haptic	7.16667	6.66533	.985	-14.8974	29.2307
		Lesson 3 Visual	28.16667*	6.66533	.004	6.1026	50.2307
		Lesson 3 Haptic	5.66667	6.66533	.997	-16.3974	27.7307
		Lesson 4 Visual	35.00000*	6.66533	.000	12.9359	57.0641
		Lesson 5 Visual	27.83333*	6.66533	.004	5.7693	49.8974

		Lesson 5 Haptic	-5.50000	6.66533	.998	-27.5641	16.5641
	Lesson 5 Visual	Lesson 1 Visual	14.33333	6.66533	.503	-7.7307	36.3974
		Lesson 1 Haptic	-19.33333	6.66533	.133	-41.3974	2.7307
		Lesson 2 Visual	12.83333	6.66533	.652	-9.2307	34.8974
		Lesson 2 Haptic	-20.66667	6.66533	.084	-42.7307	1.3974
		Lesson 3 Visual	.33333	6.66533	1.000	-21.7307	22.3974
		Lesson 3 Haptic	-22.16667*	6.66533	.048	-44.2307	-.1026
		Lesson 4 Visual	7.16667	6.66533	.985	-14.8974	29.2307
		Lesson 4 Haptic	-27.83333*	6.66533	.004	-49.8974	-5.7693
		Lesson 5 Haptic	-33.33333*	6.66533	.000	-55.3974	-11.2693
	Lesson 5 Haptic	Lesson 1 Visual	47.66667*	6.66533	.000	25.6026	69.7307
		Lesson 1 Haptic	14.00000	6.66533	.536	-8.0641	36.0641
		Lesson 2 Visual	46.16667*	6.66533	.000	24.1026	68.2307
		Lesson 2 Haptic	12.66667	6.66533	.669	-9.3974	34.7307
		Lesson 3 Visual	33.66667*	6.66533	.000	11.6026	55.7307

	Lesson 3 Haptic	11.16667	6.66533	.804	-10.8974	33.2307
	Lesson 4 Visual	40.50000*	6.66533	.000	18.4359	62.5641
	Lesson 4 Haptic	5.50000	6.66533	.998	-16.5641	27.5641
	Lesson 5 Visual	33.33333*	6.66533	.000	11.2693	55.3974

Homogeneous Subsets

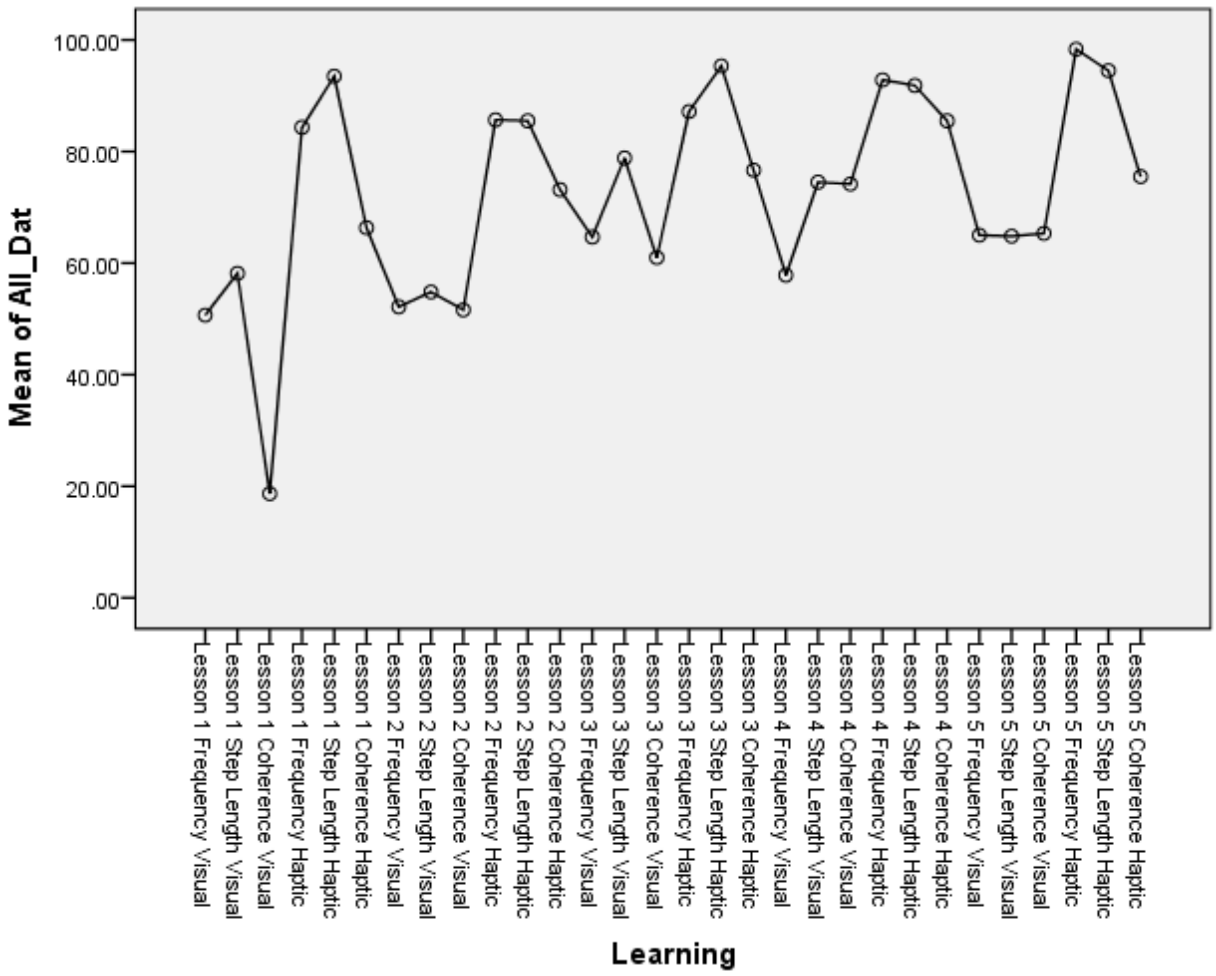
Freq_Dat

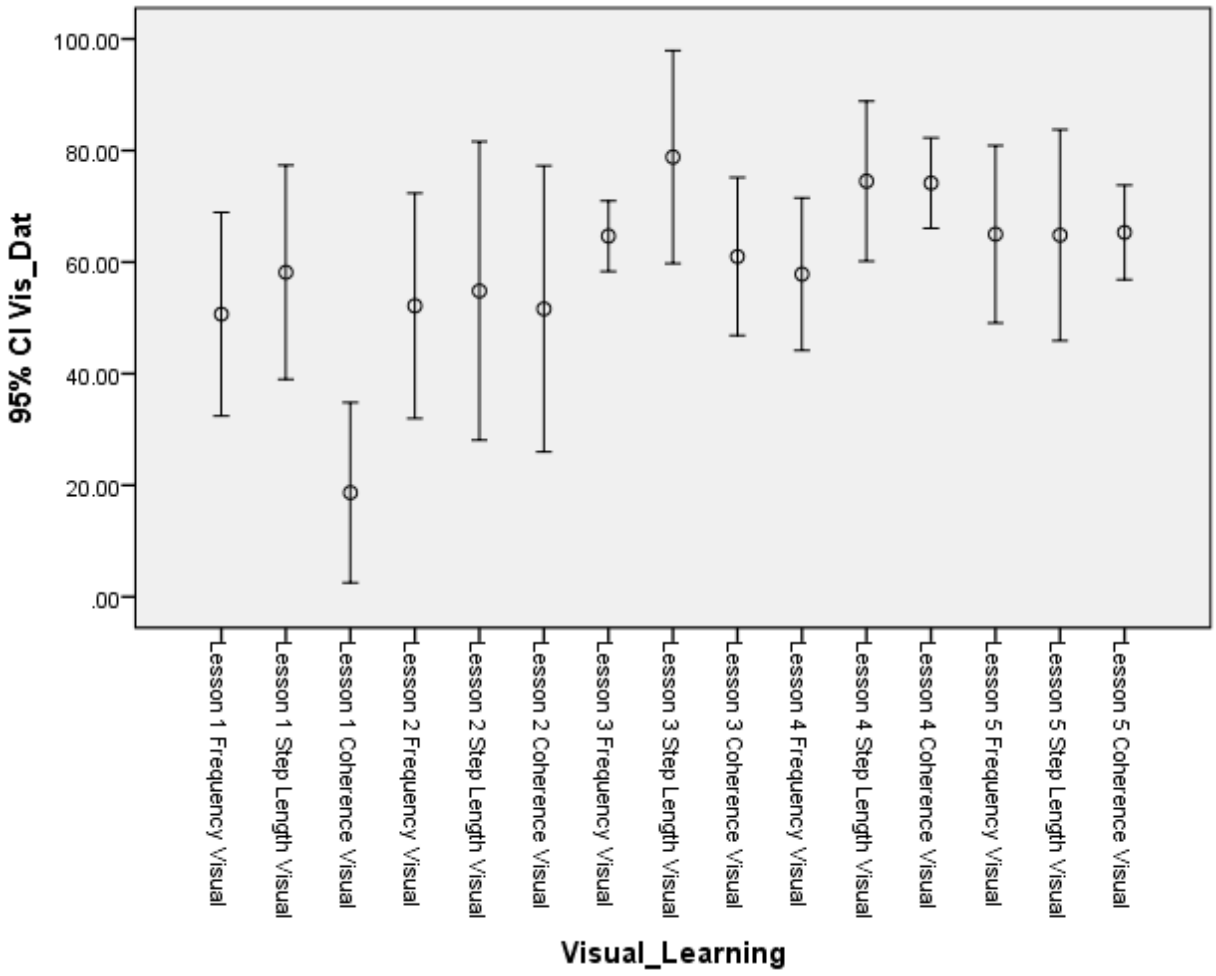
	Frequency	N	Subset for alpha = 0.05		
			1	2	3
Tukey HSD[a]	Lesson 1 Visual	6	50.6667		
	Lesson 2 Visual	6	52.1667		
	Lesson 4 Visual	6	57.8333		
	Lesson 3 Visual	6	64.6667	64.6667	
	Lesson 5 Visual	6	65.0000	65.0000	
	Lesson 1 Haptic	6		84.3333	84.3333
	Lesson 2 Haptic	6		85.6667	85.6667
	Lesson 3 Haptic	6			87.1667
	Lesson 4 Haptic	6			92.8333
	Lesson 5 Haptic	6			98.3333
	Sig.		.503	.074	.536

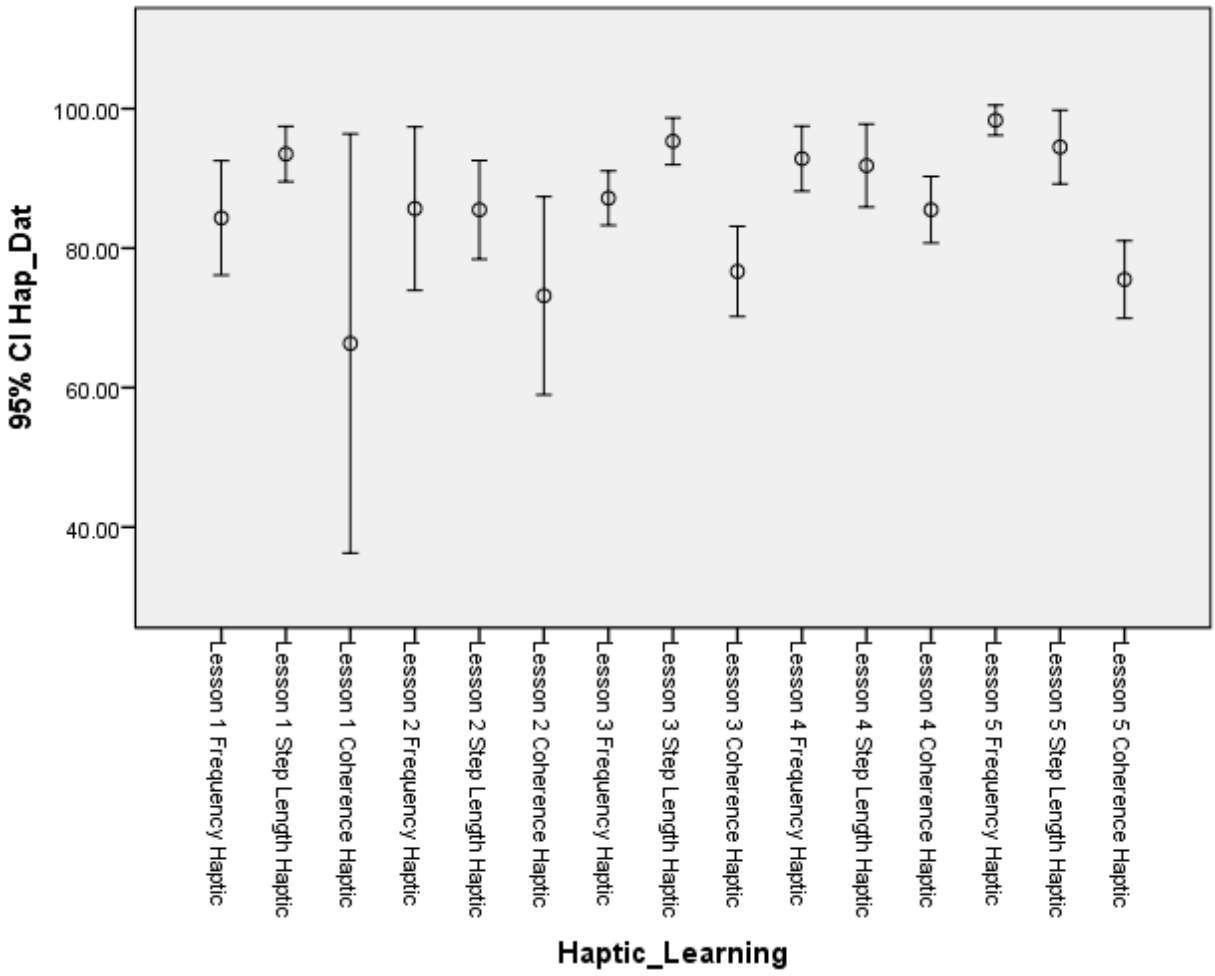
Means for groups in homogeneous subsets are displayed.

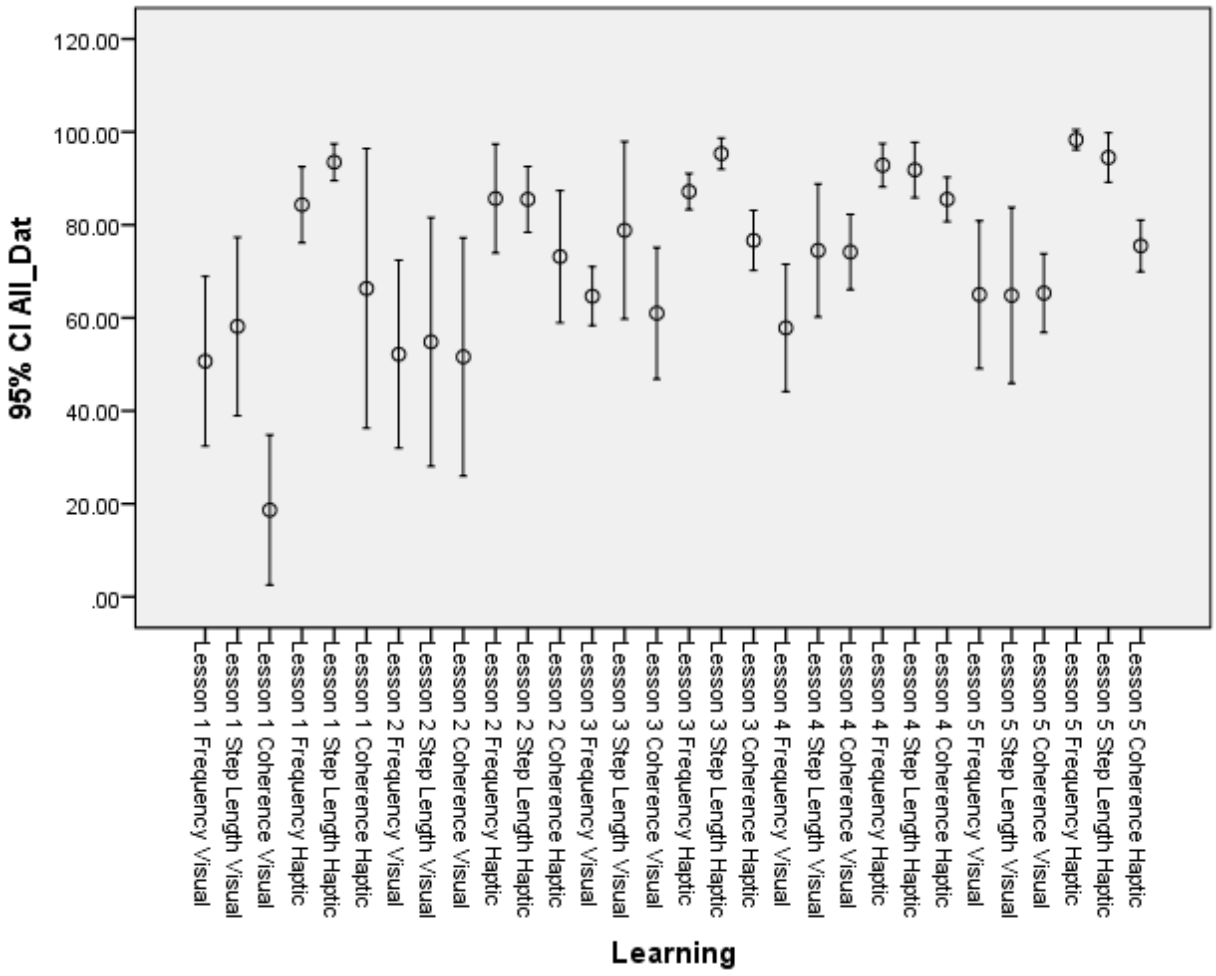
a. Uses Harmonic Mean Sample Size = 6.000.

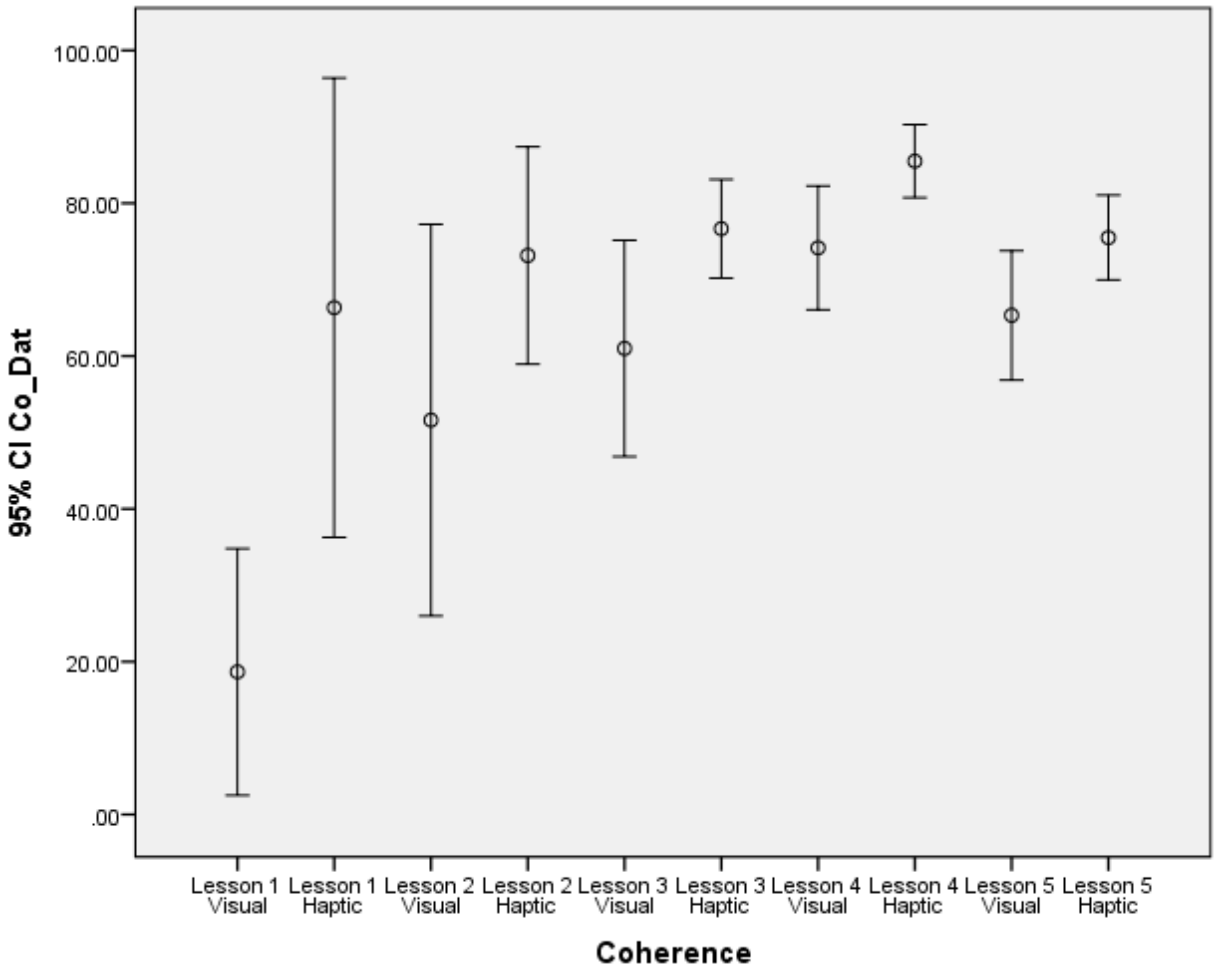
Means Plots

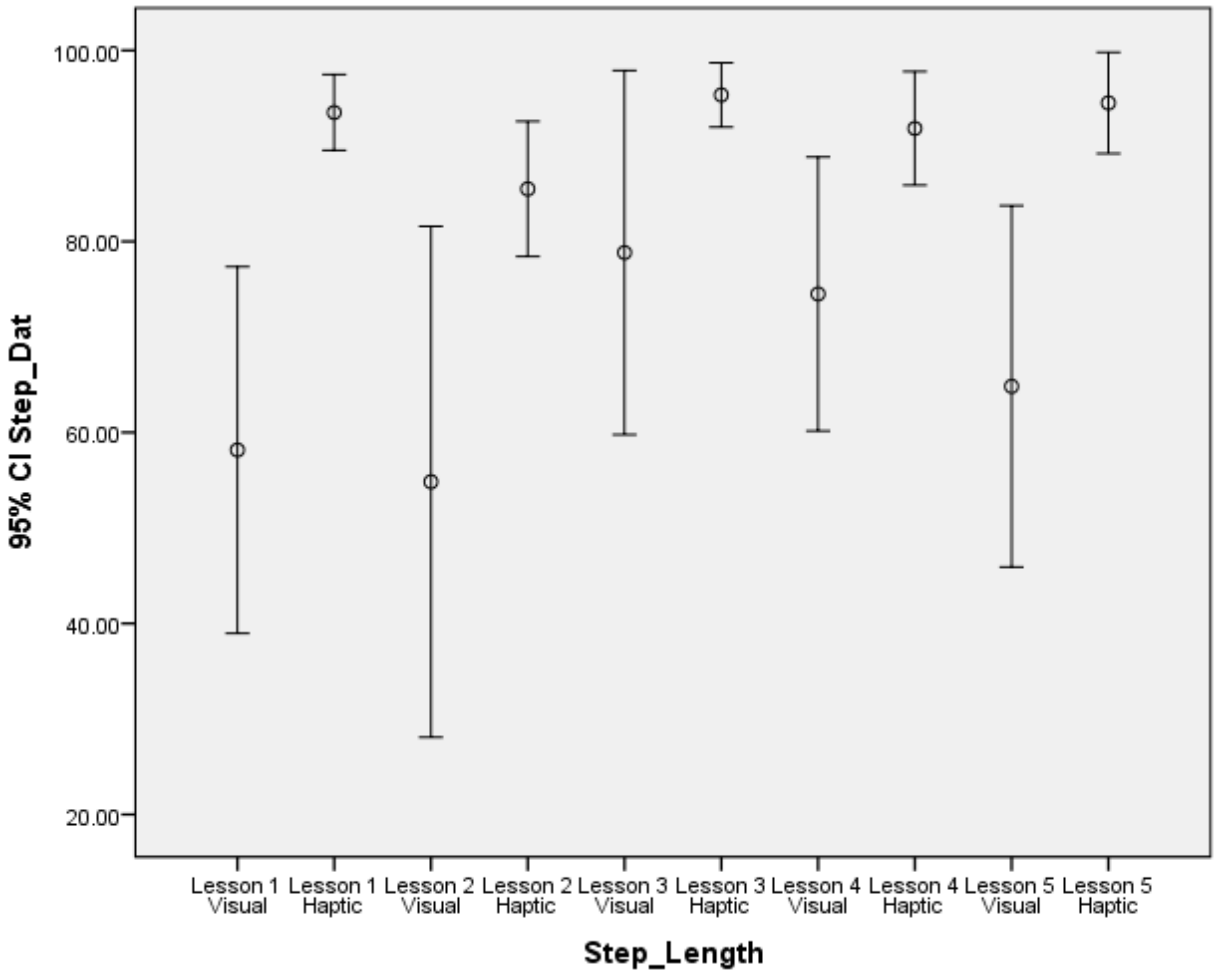

Mean of All_Dat
100.00
80.00
60.00
40.00
20.00
.00
Lesson 1 Frequency Visual
Lesson 1 Step Length Visual
Lesson 1 Coherence Visual
Lesson 1 Frequency Haptic
Lesson 1 Step Length Haptic
Lesson 1 Coherence Haptic
Lesson 2 Frequency Visual
Lesson 2 Step Length Visual
Lesson 2 Coherence Visual
Lesson 2 Frequency Haptic
Lesson 2 Step Length Haptic
Lesson 2 Coherence Haptic
Lesson 3 Frequency Visual
Lesson 3 Step Length Visual
Lesson 3 Coherence Visual
Lesson 3 Frequency Haptic
Lesson 3 Step Length Haptic
Lesson 3 Coherence Haptic
Lesson 4 Frequency Visual
Lesson 4 Step Length Visual
Lesson 4 Coherence Visual
Lesson 4 Frequency Haptic
Lesson 4 Step Length Haptic
Lesson 4 Coherence Haptic
Lesson 5 Frequency Visual
Lesson 5 Step Length Visual
Lesson 5 Coherence Visual
Lesson 5 Frequency Haptic
Lesson 5 Step Length Haptic
Lesson 5 Coherence Haptic
Learning

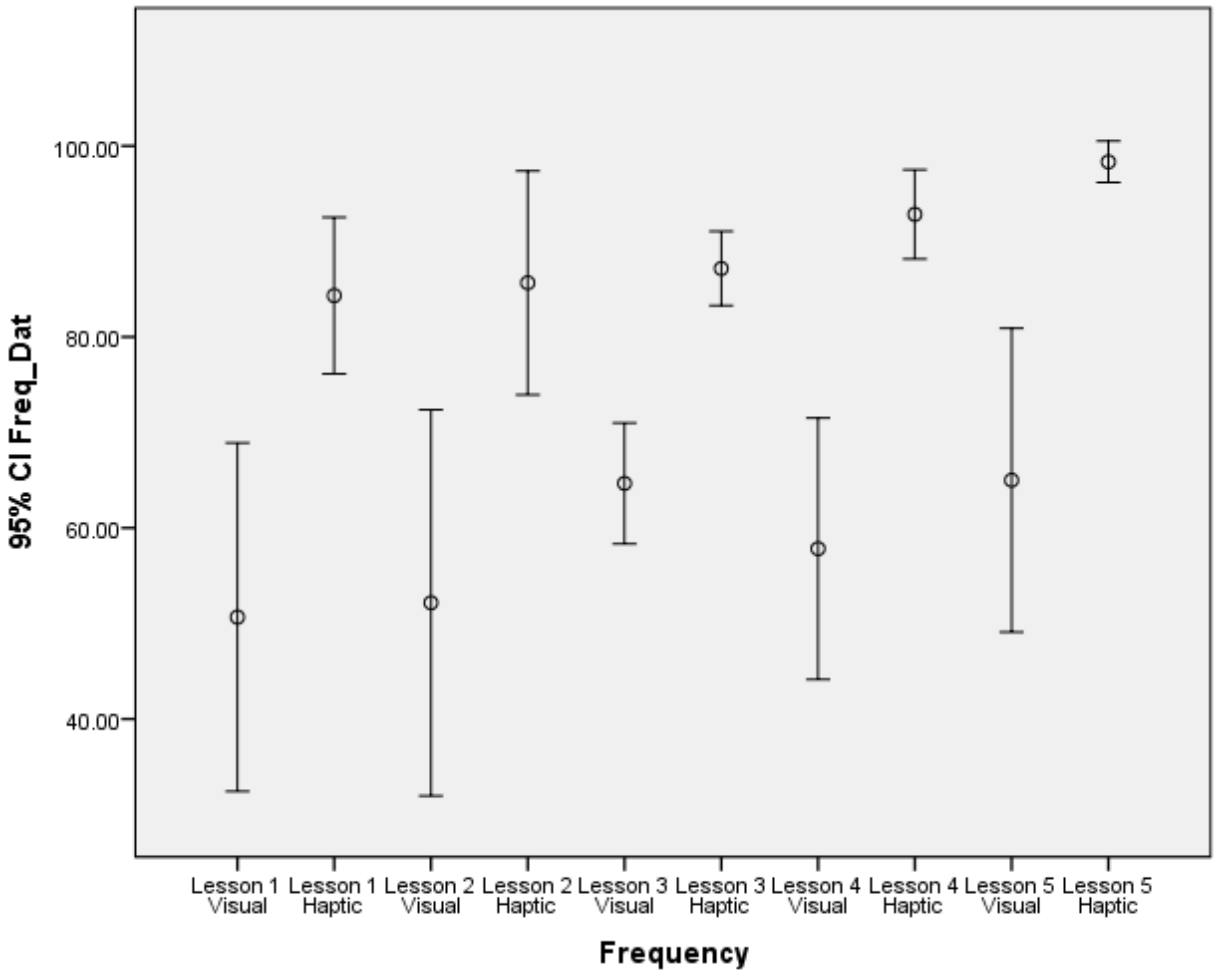

95% CI Vis_Dat
100.00
80.00
60.00
40.00
20.00
.00
Lesson 1 Frequency Visual
Lesson 1 Step Length Visual
Lesson 1 Coherence Visual
Lesson 2 Frequency Visual
Lesson 2 Step Length Visual
Lesson 2 Coherence Visual
Lesson 3 Frequency Visual
Lesson 3 Step Length Visual
Lesson 3 Coherence Visual
Lesson 4 Frequency Visual
Lesson 4 Step Length Visual
Lesson 4 Coherence Visual
Lesson 5 Frequency Visual
Lesson 5 Step Length Visual
Lesson 5 Coherence Visual
Visual_Learning


95% CI Hap_Dat
100.00
80.00
60.00
40.00
Lesson 1 Frequency Haptic
Lesson 1 Step Length Haptic
Lesson 1 Coherence Haptic
Lesson 2 Frequency Haptic
Lesson 2 Step Length Haptic
Lesson 2 Coherence Haptic
Lesson 3 Frequency Haptic
Lesson 3 Step Length Haptic
Lesson 3 Coherence Haptic
Lesson 4 Frequency Haptic
Lesson 4 Step Length Haptic
Lesson 4 Coherence Haptic
Lesson 5 Frequency Haptic
Lesson 5 Step Length Haptic
Lesson 5 Coherence Haptic
Haptic_Learning


95% CI All_Dat
120.00
100.00
80.00
60.00
40.00
20.00
.00
Learning
Lesson 1 Frequency Visual
Lesson 1 Step Length Visual
Lesson 1 Coherence Visual
Lesson 1 Frequency Haptic
Lesson 1 Step Length Haptic
Lesson 1 Coherence Haptic
Lesson 2 Frequency Visual
Lesson 2 Step Length Visual
Lesson 2 Coherence Visual
Lesson 2 Frequency Haptic
Lesson 2 Step Length Haptic
Lesson 2 Coherence Haptic
Lesson 3 Frequency Visual
Lesson 3 Step Length Visual
Lesson 3 Coherence Visual
Lesson 3 Frequency Haptic
Lesson 3 Step Length Haptic
Lesson 3 Coherence Haptic
Lesson 4 Frequency Visual
Lesson 4 Step Length Visual
Lesson 4 Coherence Visual
Lesson 4 Frequency Haptic
Lesson 4 Step Length Haptic
Lesson 4 Coherence Haptic
Lesson 5 Frequency Visual
Lesson 5 Step Length Visual
Lesson 5 Coherence Visual
Lesson 5 Frequency Haptic
Lesson 5 Step Length Haptic
Lesson 5 Coherence Haptic


100.00
80.00
60.00
40.00
20.00
.00
95% CI Co_Dat
Lesson 1 Visual
Lesson 1 Haptic
Lesson 2 Visual
Lesson 2 Haptic
Lesson 3 Visual
Lesson 3 Haptic
Lesson 4 Visual
Lesson 4 Haptic
Lesson 5 Visual
Lesson 5 Haptic
Coherence


100.00
80.00
60.00
40.00
20.00
95% CI Step_Dat
Lesson 1 Visual
Lesson 1 Haptic
Lesson 2 Visual
Lesson 2 Haptic
Lesson 3 Visual
Lesson 3 Haptic
Lesson 4 Visual
Lesson 4 Haptic
Lesson 5 Visual
Lesson 5 Haptic
Step_Length


95% CI Freq_Dat
100.00
80.00
60.00
40.00
Lesson 1 Visual
Lesson 1 Haptic
Lesson 2 Visual
Lesson 2 Haptic
Lesson 3 Visual
Lesson 3 Haptic
Lesson 4 Visual
Lesson 4 Haptic
Lesson 5 Visual
Lesson 5 Haptic
Frequency

B. MATLAB Codes

1. Limb Calibration (Plot and Save)

```
%% SCRIPT TO SAVE CALIBRATION FILES  %%
%% Use CaptureRawSignals.mdl to generate data

% A full set of calibration should contain:
% 1) 2 or more baseline trials (sensors at rest, not attached to subject)
% 2) 1 potentiometer trial (potentiometer should be cycled through entire range of motion several times)
% 3) 2 or more EMG baseline trials (sensors and ground applied to subject)
% 4) 2 or more Flexion trials
% 5) Extension test with the same number of trials as for the Flexion test

%% PLOT MSU-A AND MSU-B SIGNALS
figure(1)
hold on
subplot(411), plot(sEMG12(:,2:3)), xlabel('Sample'), ylabel('Signal [volts]'), title('sEMG');
subplot(412), plot(Pressure12(:,2:3)), xlabel('Sample'), ylabel('Signal [volts]'), title('Normal Pressure');
subplot(413), plot(Axial12(:,2:3)), xlabel('Sample'), ylabel('Signal [volts]'), title('Axial Shear');
subplot(414), plot(Transverse12(:,2:3)), xlabel('Sample'), ylabel('Signal [volts]'), title('Transverse Shear');
hold off

%% SAVE MSU AND LEG SIGNALS - Baseline (SENSORS AT REST)
trial = 2;
Filename1 = ['baselineLegPat' num2str(trial)];
save(Filename1, '*12', 'theta', 'omega', 'force', 'foot')

%% SAVE MSU AND LEG SIGNALS - Potentiometer (CYCLE THROUGH TRAVEL RANGE)
trial = 1;
Filename1 = ['PotCal' num2str(trial)];
save(Filename1, 'theta', 'omega')

%% SAVE MSU AND LEG SIGNALS - sEMG Baseline (Sensors in operation/test configuration on subject)
trial = 2;
Filename1 = ['baselineEMG' num2str(trial)];
save(Filename1, 'sEMG12')

%% SAVE MSU AND LEG SIGNALS - Flexion Trials
trial = 2;
Filename1 = ['flex' num2str(trial)];
save(Filename1, '*12', 'theta', 'omega', 'force', 'foot')

%% SAVE MSU AND LEG SIGNALS - Extension Trials
trial = 2;
Filename1 = ['ext' num2str(trial)];
save(Filename1, '*12', 'theta', 'omega', 'force', 'foot')
```

2. Limb Calibration (Calibration Code for PCA)

```
%% BASELINE CALIBRATION FOR PROSTHETIC LEG ELECTRONICS
close all
clear
clc

filenames1 = filenamegen('baselineEMG*.mat');

%% Build arrays of data for all trials
r = 1;
for n1 = 1:length(filenames1)
   load(filenames1{n1})
   if r == 1
      sEMGflx1 = sEMG12(:,3);
      sEMGext1 = sEMG12(:,2);
      r = r+1;
   else
      sEMGflx1 = [sEMGflx1 sEMG12(:,3)];
      sEMGext1 = [sEMGext1 sEMG12(:,2)];
   end
end
clear sEMG12 theta omega force foot n1 r1

%% Filter Signal FIR order 150
% Wc is the normalized Cutoff frequency between 0 and 1 where 1 is the
% nyquist frequency
n = 150;        % Filter Order
Fc = .5;        % Cutoff frequency [Hz]
Fs = 1000;      % Sampling Frequency
Fn = Fs/2;      % Nyquist Frequency
Wn = Fc/Fn;     % Normalized cutoff frequency
b = fir1(n,Wn); % Digital FIR Filter Coefficients
a = [1];

% Apply Filter
sEMGflx2 = filter(b,a,sEMGflx1);
sEMGext2 = filter(b,a,sEMGext1);


%% Generate Signal Bias and MVC Scaling Values Values
n = 100;
r=1;
for n2 = n:n:length(sEMGflx2(:))
   sEMGflx2b(:,r) = min(sEMGflx2(n2-n+1:n2));
   sEMGext2b(:,r) = min(sEMGext2(n2-n+1:n2));
   r = r+1;
end

%% Running Average Filter
n = 100;
a = 1;
b = ones(1,n)/n;
sEMGflx2r = filter(b,a,sEMGflx2b);
sEMGext2r = filter(b,a,sEMGext2b);
```

```
%% Plot Trials Consecutively To See Trends
figure()
hold on, plot([sEMGflx2(:) sEMGext2(:)]),
plot(ones(size(sEMGflx2(:)))*sEMGflx2r(length(sEMGflx2r)),'m'),
plot(ones(size(sEMGext2(:)))*sEMGext2r(length(sEMGext2r)),'c'), title('sEMG Signals'), grid on, axis
tight, hold off;

%% Subtract Biases

% Define Biases
sEMGflxb = sEMGflx2r(length(sEMGflx2r));
sEMGextb = sEMGext2r(length(sEMGext2r));

% Subtract Biases
sEMGflx2 = sEMGflx2 - sEMGflxb;
sEMGext2 = sEMGext2 - sEMGextb;


% figure()
% hold on
% plot([sEMGflx2(:) sEMGext2(:)])
% title('sEMG Signals')
% grid on
% axis tight
% hold off;

save('SignalBiasesEMG', 'sEMGflxb', 'sEMGextb')
clear


%% Scale sEMG Flexion Signals
load('SignalBiasesEMG')
filenames2 = filenamegen('flex*.mat');

% Build arrays of data for all trials
r = 1;
for n1 = 1:length(filenames2)
   load(filenames2{n1})
   if r == 1
      sEMGflx1 = sEMG12(:,3);
      sEMGext1 = sEMG12(:,2);
      r = r+1;
   else
      sEMGflx1 = [sEMGflx1 sEMG12(:,3)];
      sEMGext1 = [sEMGext1 sEMG12(:,2)];
   end
end


% Scale sEMG Extensor Signals
filenames3 = filenamegen('ext*.mat');

% Build arrays of data for all trials
r = 1;
for n1 = 1:length(filenames3)
   load(filenames3{n1})
   if r == 1
```

```
        sEMGflx2 = sEMG12(:,3);
        sEMGext2 = sEMG12(:,2);
        r = r+1;
    else
        sEMGflx2 = [sEMGflx2 sEMG12(:,3)];
        sEMGext2 = [sEMGext2 sEMG12(:,2)];
    end
end

% Bias Subtraction
sEMGflx1 = sEMGflx1 - sEMGflxb;
sEMGext1 = sEMGext1 - sEMGextb;
sEMGflx2 = sEMGflx2 - sEMGflxb;
sEMGext2 = sEMGext2 - sEMGextb;

% MVC Scaling Calculations
Sflx = max([sEMGflx1(:); sEMGflx2(:)]);
Sext = max([sEMGext1(:); sEMGext2(:)]);

% Scale sEMG Signals
sEMGflx1 = sEMGflx1/Sflx;
sEMGflx2 = sEMGflx2/Sflx;
sEMGext1 = sEMGext1/Sext;
sEMGext2 = sEMGext2/Sext;

% Plot Results
figure()
hold on
plot(sEMGflx1(:), sEMGext1(:),'r')
plot(sEMGflx2(:), sEMGext2(:),'b')
xlabel('Flexion')
ylabel('Extension')
title('Calibration Data')
legend('Flexion Data', 'Extension Data')
grid on
axis tight
hold off


save('SignalScalingEMG', 'Sflx', 'Sext')
clear *12

%% --- Discriminant Analysis --- %%

% Thresholding
thresh1 = 0.05;
thresh2 = 0.0;
% Find all Flexion Data points above thresh1
[a1] = find(sEMGflx1(:) > thresh1);
% Find all Extension Data points above thresh1
[a2] = find(sEMGext2(:) > thresh1);


% Define Groups for Classification
Group1 = cell(size(a1));
Group1(:) = {'Flexion'};
Group2 = cell(size(a2));
Group2(:) = {'Extension'};
Group3 = [Group1; Group2];
```

```
%clear Group1 Group2

% Perform Classification - Linear
figure()
hold on
type1 = 'linear';
type2 = 'quadratic';
axext = [-0.01 1.01 -0.01 1.01];

h1 = gscatter([sEMGflx1(a1); sEMGflx2(a2)],[sEMGext1(a1);
sEMGext2(a2)],Group3,'rb','',[],'off');
set(h1,'LineWidth',1)
legend('Flexion','Extension','Location','NW')

[X1,Y1] = meshgrid(linspace(axext(1),axext(2)), linspace(axext(3),axext(4)));
X1 = X1(:); Y1 = Y1(:);
Sample1 = [X1,Y1];

[C1,err1,P1,logp1,coeff1] = classify(Sample1,[sEMGflx1(a1) sEMGext1(a1); sEMGflx2(a2)
sEMGext2(a2)], Group3, type1);

hold on;
gscatter(Sample1(:,1),Sample1(:,2),C1,'rb','',1,'off');
K1 = coeff1(1,2).const;
L1 = coeff1(1,2).linear;
%Q = coeff1(1,2).quadratic;
% Function to compute K + L*v + v'*Q*v for multiple vectors
% v=[x;y]. Accepts x and y as scalars or column vectors.
f = @(x,y) K1 + [x y]*L1; % + sum(([x y]*Q) .* [x y], 2);

h2 = ezplot(f,axext);
set(h2,'Color','m','LineWidth',2)
axis(axext)
xlabel('Flexion Potential')
ylabel('Extension Potential')
title('{\bf Flexor/Extensor Classification - Linear}')
hold off

% Perform Classification - Quadratic
figure()
hold on
h1 = gscatter([sEMGflx1(a1); sEMGflx2(a2)],[sEMGext1(a1);
sEMGext2(a2)],Group3,'rb','',[],'off');
set(h1,'LineWidth',1)
legend('Flexion','Extension','Location','NW')

[X1,Y1] = meshgrid(linspace(axext(1),axext(2)), linspace(axext(3),axext(4)));
X1 = X1(:); Y1 = Y1(:);
Sample1 = [X1,Y1];

[C2,err2,P2,logp2,coeff2] = classify(Sample1,[sEMGflx1(a1) sEMGext1(a1); sEMGflx2(a2)
sEMGext2(a2)], Group3, type2);

hold on;
gscatter(Sample1(:,1),Sample1(:,2),C2,'rb','',1,'off');
K2 = coeff2(1,2).const;
L2 = coeff2(1,2).linear;
Q2 = coeff2(1,2).quadratic;
% Function to compute K + L*v + v'*Q*v for multiple vectors
```

```
% v=[x;y]. Accepts x and y as scalars or column vectors.
f = @(x,y) K2 + [x y]*L2 + sum(([x y]*Q2) .* [x y], 2);

h2 = ezplot(f,axext);
set(h2,'Color','m','LineWidth',2)
axis(axext)
xlabel('Flexion Potential')
ylabel('Extension Potential')
title('{\bf Flexor/Extensor Classification - Quadratic}')
hold off

%% PCA - Transform
% PCA ANALYSIS - Flexion
% Perform PCA On Bias Subtracted and Scaled Signal
[pc1,score1,latent1,tsquare1] = princomp([sEMGflx1(:) sEMGext1(:); -sEMGflx1(:) -
sEMGext1(:)]);
cum1 = cumsum(latent1)./sum(latent1);
PCATransFlx = pc1;

% Plot Flexion PCA - Original and Transform
figure()
[a,b] = size(score1);
plot(sEMGflx1(:), sEMGext1(:),'b',(score1(1:a/2,1)),(score1(1:a/2,2)),'r')
xlabel('Flexor / C1')
ylabel('Extensor / C2')
title('PCA of Socket Flexion Data')
legend('Original', 'Transform')
grid on
axis equal;

% PCA ANALYSIS - Extension
% Perform PCA On Bias Subtracted and Scaled Signal
[pc2,score2,latent2,tsquare2] = princomp([sEMGflx2(:) sEMGext2(:); -sEMGflx2(:) -
sEMGext2(:)]);
cum2 = cumsum(latent2)./sum(latent2);
PCATransExt = pc2;

% Plot Extension PCA - Original and Transform
figure()
[a,b] = size(score2);
plot(sEMGflx2(:), sEMGext2(:),'b',(score2(1:a/2,1)),(score2(1:a/2,2)),'r')
xlabel('Flexor / C1')
ylabel('Extensor / C2')
title('PCA of Socket Extension Data')
legend('Original', 'Transform')
grid on
axis equal;

save('DAPCA', 'PCATransExt', 'PCATransFlx', 'K*', 'L*', 'Q*')


%% Curve Fits via PCA
xflx = linspace(0,1);
xext = -linspace(0,1);
XYflx = [xflx;zeros(size(xflx))];
XYext = [xext;zeros(size(xext))];

for p = 1:length(xflx)
   Aflx(:,p) = pc1'*XYflx(:,p);
```

```
    Aext(:,p) = pc2'*XYext(:,p);
end

figure()
hold on
plot(sEMGflx1(:),sEMGext1(:),'r',sEMGflx2(:),sEMGext2(:),'b');
plot(Aflx(1,:),-Aflx(2,:),'c','Linewidth',3)
plot(Aext(1,:),-Aext(2,:),'g','Linewidth',3)
% plot(Aext(1,:)-(-Aflx(1,:)),-(Aext(2,:)-(-Aflx(2,:))),'m','Linewidth',4)
plot(Aext(1,:)-(-Aflx(1,:)),-(Aext(2,:)-(-Aflx(2,:))),'m','Linewidth',4)
xlabel('Flexion')
ylabel('Extension')
legend('Flexion Data', 'Extension Data', 'Flexion Mean', 'Extension Mean', 'Flx/Ext Boundary')
grid on
xlim([-.1,1.1])
ylim([-.1,1.1])

B = [Aext(1,:)-(-Aflx(1,:)); -Aext(2,:)-(-Aflx(2,:))];
mb = B(2,100)/B(1,100);
mflx = -Aflx(2,100)/Aflx(1,100);
mext = -Aext(2,100)/Aext(1,100);

% compute average slope from mext and mflx
theta_ext = atan(1/mext);
theta_flx = atan(1/mflx);
theta_avg = (theta_ext+theta_flx)/2;
mavg = tan(theta_avg);

save('ImpPars', 'mb', 'mavg', 'mflx', 'mext', 'L*', 'Q*')


%% BASELINE CALIBRATIONS FOR PRESSURE AXIAL AND TRANSVERSE SIGNALS
clear
filenames4 = filenamegen('b*LegPat*.mat');

%% Build arrays of data for all trials
r = 1;
for n1 = 1:length(filenames4)
    load(filenames4{n1})
    if r == 1
%         axialflx1 = Axial12(:,3);
%         axialext1 = Axial12(:,2);
%         pressflx1 = Pressure12(:,3);
%         pressext1 = Pressure12(:,2);
%         transflx1 = Transverse12(:,3);
%         transext1 = Transverse12(:,2);
        theta1 = theta(:,2);
        omega1 = omega(:,2);
        force1 = force(:,2);
        heel1 = foot(:,2);
        toe1 = foot(:,3);
        r = r+1;
    else
%         axialflx1 = [axialflx1 Axial12(:,3)];
%         axialext1 = [axialext1 Axial12(:,2)];
%         pressflx1 = [pressflx1 Pressure12(:,3)];
%         pressext1 = [pressext1 Pressure12(:,2)];
%         transflx1 = [transflx1 Transverse12(:,3)];
%         transext1 = [transext1 Transverse12(:,2)];
```

```
        theta1 = [theta1 theta(:,2)];
        omega1 = [omega1 omega(:,2)];
        force1 = [force1 force(:,2)];
        heel1 = [heel1 foot(:,2)];
        toe1 = [toe1 foot(:,3)];
    end
end
clear *12 theta omega force foot

%% Filter Signal FIR order 150
% Wc is the normalized Cutoff frequency between 0 and 1 where 1 is the
% nyquist frequency
n = 150;        % Filter Order
Fc = .5;        % Cutoff frequency [Hz]
Fs = 1000;      % Sampling Frequency
Fn = Fs/2;      % Nyquist Frequency
Wn = Fc/Fn;     % Normalized cutoff frequency
b = fir1(n,Wn); % Digital FIR Filter Coefficients
a = [1];

% Apply Filter
% axialflx2 = filter(b,a,axialflx1);
% axialext2 = filter(b,a,axialext1);
% pressflx2 = filter(b,a,pressflx1);
% pressext2 = filter(b,a,pressext1);
% transflx2 = filter(b,a,transflx1);
% transext2 = filter(b,a,transext1);
theta2 = filter(b,a,theta1);
omega2 = filter(b,a,omega1);
force2 = filter(b,a,force1);
heel2 = filter(b,a,heel1);
toe2 = filter(b,a,toe1);

clear *1

%% Generate Means
n = 500;
a = 1;
b = ones(1,n)/n;
% axialflx2m = filter(b,a,axialflx2(:));
% axialext2m = filter(b,a,axialext2(:));
% pressflx2m = filter(b,a,pressflx2(:));
% pressext2m = filter(b,a,pressext2(:));
% transflx2m = filter(b,a,transflx2(:));
% transext2m = filter(b,a,transext2(:));
theta2m = filter(b,a,theta2(:));
omega2m = filter(b,a,omega2(:));
force2m = filter(b,a,force2(:));
heel2m = filter(b,a,heel2(:));
toe2m = filter(b,a,toe2(:));

% axialflx2m = axialflx2m(length(axialflx2m));
% axialext2m = axialext2m(length(axialext2m));
% pressflx2m = pressflx2m(length(pressflx2m));
% pressext2m = pressext2m(length(pressext2m));
% transflx2m = transflx2(length(transflx2m));
% transext2m = transext2m(length(transext2m));
theta2m = theta2m(length(theta2m));
omega2m = omega2m(length(omega2m));
```

```
force2m = force2m(length(force2m));
heel2m = heel2m(length(heel2m));
toe2m = toe2m(length(toe2m));

% save('SignalBiasesPAT', '*flx2m', '*ext2m')
save('SignalBiasesLEG', 'theta2m', 'omega2m', 'force2m', 'heel2m', 'toe2m')

%% Plot Trials Consecutively To See Trends
% figure()
% subplot(311), hold on, plot([axialflx2(:) axialext2(:)]),
plot(ones(size(axialflx2(:)))*axialflx2m(length(axialflx2m)),'m'),
plot(ones(size(axialext2(:)))*axialext2m(length(axialext2m)),'c'), title('Axial Signals'), axis tight, hold off;
% subplot(312), hold on, plot([pressflx2(:) pressext2(:)]),
plot(ones(size(pressflx2(:)))*pressflx2m(length(pressflx2m)),'m'),
plot(ones(size(pressext2(:)))*pressext2m(length(pressext2m)),'c'), title('Pressure Signals'), axis tight,
hold off;
% subplot(313), hold on, plot([transflx2(:) transext2(:)]),
plot(ones(size(transflx2(:)))*transflx2m(length(transflx2m)),'m'),
plot(ones(size(transext2(:)))*transext2m(length(transext2m)),'c'), title('Transverse Signals'), axis tight,
hold off;


%% Subtract Biases
% axialflx2 = axialflx2 - axialflx2m;
% axialext2 = axialext2 - axialext2m;
% pressflx2 = pressflx2 - pressflx2m;
% pressext2 = pressext2 - pressext2m;
% transflx2 = transflx2 - transflx2m;
% transext2 = transext2 - transext2m;
theta2 = theta2 - theta2m;
omega2 = omega2 - omega2m;
force2 = force2 - force2m;
heel2 = heel2 - heel2m;
toe2 = toe2 - toe2m;

%
% figure()
% subplot(711), hold on, plot([axialflx2(:) axialext2(:)]), title('sEMG Signals'), axis tight, hold
off;
% subplot(712), hold on, plot([pressflx2(:) pressext2(:)]), title('sEMG Signals'), axis tight, hold
off;
% subplot(713), hold on, plot([transflx2(:) transext2(:)]), title('sEMG Signals'), axis tight, hold
off;
% subplot(714), hold on, plot([theta2(:)]), title('sEMG Signals'), axis tight, hold off;
% subplot(715), hold on, plot([omega2(:)]), title('sEMG Signals'), axis tight, hold off;
% subplot(716), hold on, plot([force2(:)]), title('sEMG Signals'), axis tight, hold off;
% subplot(717), hold on, plot([heel2(:) toe2(:)]), title('sEMG Signals'), axis tight, hold off;



%% BASELINE CALIBRATIONS FOR PRESSURE AXIAL AND TRANSVERSE SIGNALS
clear
load('PotCal1.mat')
thetamin = 0;
thetamax = pi/2;

%% Filter Signal FIR order 150
% Wc is the normalized Cutoff frequency between 0 and 1 where 1 is the
% nyquist frequency
```

```
n = 150;        % Filter Order
Fc = .5;        % Cutoff frequency [Hz]
Fs = 1000;      % Sampling Frequency
Fn = Fs/2;      % Nyquist Frequency
Wn = Fc/Fn;     % Normalized cutoff frequency
b1 = fir1(n,Wn); % Digital FIR Filter Coefficients
a1 = [1];

% Apply Filter
theta2 = filter(b1,a1,theta(:,2));
[a,b] = size(theta2);
% Find Min and Max
vmin = min(theta2(Fs:a-Fs));
vmax = max(theta2(Fs:a-Fs));
theta2m = vmin;

volts2rad = (thetamax-thetamin)/(vmax - vmin);

figure()
hold on
plot([theta(:,2) theta2])
plot(ones(1,length(theta2))*vmin,'r')
plot(ones(1,length(theta2))*vmax,'m')
legend('Raw','FIR','Min','Max')
grid on
hold off

save('FIRCoeffs', 'a1', 'b1')
save('SignalBiasPot', 'theta2m', 'volts2rad', 'vmin', 'vmax')
```

3. Correlator (MSC Coherence)

```
clear F Cxy MatchingFreqs figure(1)


Fs = 1000;        % Sampling Rate
L = 30000;         %samples after trimmer, note should be 30,000

[MaxValue,IndexMax] = max(abs(fft(ThetaDesiredvsThetaPerformed(1:30000,3)-
mean(ThetaDesiredvsThetaPerformed(1:30000,3)))));

[Cxy,F] = mscohere(ThetaDesiredvsThetaPerformed(1:30000,3),LoopTheta(1:30000,end),Fs);

MatchingFreqs = IndexMax*Fs/L;

disp(MatchingFreqs);

figure(1)
plot(F,Cxy);
hold on
plot(LoopTheta(1:30000,end))
plot(ThetaDesiredvsThetaPerformed(1:30000,end))
hold off

figure(2)
plot(Cxy(:,end))
```

4. Peak_Counter

```
clear StepCount1 StepCount2 figure(1)

Fs = 1000;        % Sampling Rate
L = 30000;        %samples after trimmer, note should be 30,000

StepCount1 = 0;
StepCount2 = 0;
NuTheta = ThetaDesiredvsThetaPerformed(1:30000,3);
NuLoopTheta = LoopTheta(1:30000,2);
Looplim = .9;
Actlim = .5;
NuTMax = max(NuTheta);
NuLTMax = max(NuLoopTheta);
for k = 2:length(NuTheta)-1
   if (NuTheta(k) > NuTheta(k-1) && NuTheta(k)>NuTheta(k+1) &&
(NuTheta(k)/NuTMax)>Actlim)
      StepCount1 = StepCount1+1;
   end
end

for k = 2:length(NuLoopTheta)-1
   if (NuLoopTheta(k) > NuLoopTheta(k-1) && NuLoopTheta(k)>NuLoopTheta(k+1) &&
(NuLoopTheta(k)/NuLTMax)>Looplim)
      StepCount2 = StepCount2+1;
   end
end

N = length(NuTheta);
ts = N/Fs;

SPS1 = StepCount1/ts;
SPS2 = StepCount2/ts;

if SPS1 > SPS2
   Accuracy = SPS2/SPS1;
else
   Accuracy = SPS1/SPS2;
end

disp(Accuracy);
figure(1)
plot(LoopTheta(1:30000,end))
hold on
plot(ThetaDesiredvsThetaPerformed(1:30000,3))
```

5. Knee Angle Ensemble Average

```
%% GaitEnsemble.m
%
% Your gait data is in e
% ns=sampling frequency % nd distance from the first swing peak
e=ThetaDesiredvsThetaPerformed(1:35000,3);
ns=1000;
nd=500;
nf = 1; % start location for FIRST peak
% find 1st peak
% a=amplitude
% nmax= index corresponding to peak
[a,nmax]=max(e(nf:ns));
j=1;
nb=[];
nb(j)=nmax;
% find rest of the peaks
nend=nb(j)+nd+ns;

while nb(j)+nd+ns < length(e);
   nstart=nb(j)+nd;
   nend=nstart+ns;
   [a,nmax]=max(e(nstart:nend));
   j=j+1;
   nb(j)=nmax+nstart-1;
end

% plot results
n=1:length(e);
figure;
plot(n,e,nb,e(nb),'ro');
axis tight

%% ensemble average
Nb=length(nb);                % the number of strides detected
nperiod=mean(diff(nb));       % find the average gait period
nint=round(1.1*nperiod);      % chose a gait cycle interval slightly longer than nperiod
pens=zeros(Nb-1,nint);
for n=1:Nb-1
   pens(n,:)=e(nb(n):nb(n)+nint-1,1);
end
pensavg=mean(pens);      % ensemble average
penssd=std(pens);        %    and standard deviation

figure
for n=1:Nb-1
plot(pens(n,:))
hold on
end

figure
plot(pensavg(1,:))

%% Loop Knee Data

%% DesiredGaitEnsemble.m
```

```
%
% Your gait data is in e
% ns=sampling frequency % nd distance from the first peak
b=LoopTheta(1:35000,end);
fs=1000;
fd=500;
ff = 1; % LOC of first peak
% find 1st peak
% a=amplitude
% nmax= index corresponding to maximum peak
[a,fmax]=max(b(1:fs));
k=1;
fb=[];
fb(k)=fmax;
% find rest of the peaks
fend=fb(k)+fd+fs;
while fb(k)+fd+fs < length(b);
   fstart=fb(k)+fd;
   fend=fstart+fs;
   [a,fmax]=max(b(fstart:fend));
   k=k+1;
   fb(k)=fmax+fstart-1;
end
% plot results
f=1:length(b);
figure;
plot(f,b,fb,b(fb),'ro');
axis tight

%% ensemble average
Fb=length(fb);              % the number of strides detected
fperiod=mean(diff(fb));       % find the average gait period
fint=round(1.1*fperiod);      % chose a gait cycle interval slightly longer than nperiod
fens=zeros(Fb-1,fint);
for f=1:Fb-1
   fens(f,:)=b(fb(f):fb(f)+fint-1,1);
end
fensavg=mean(fens);      % ensemble average
fenssd=std(fens);        %    and standard deviation

figure
for f=1:Fb-1
plot(fens(f,:))
hold on
end

figure
plot(fensavg(1,:))


figure
subplot(2,1,1)
plot(fensavg(1,250:end))
subplot(2,1,2)
plot(pensavg(1,250:end))
```

6. Torque Ensemble Average

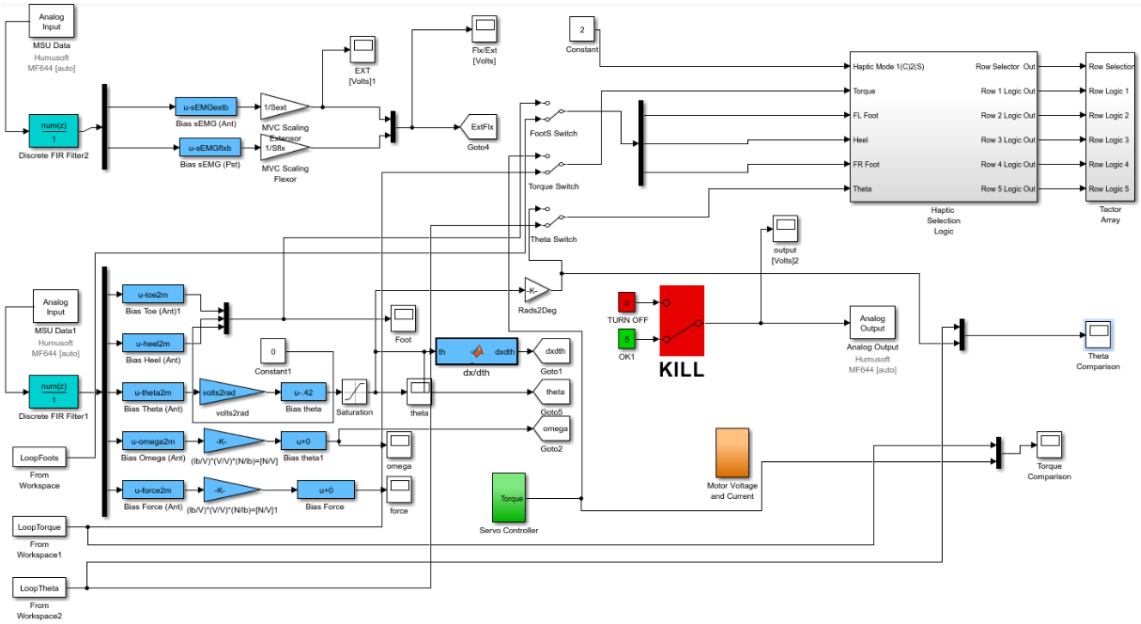
```
%% GaitEnsemble.m
        %
        % Your gait data is in e
        % ns=sampling frequency % nd distance from the first swing peak
        e=TorqueDesired(1:35000,end);
        ns=1000;
        nd=500;
        nf = 1; % start location for FIRST peak
        % find 1st peak
        % a=amplitude
        % nmax= index corresponding to peak
        [a,nmax]=max(e(nf:ns));
        j=1;
        nb=[];
        nb(j)=nmax;
        % find rest of the peaks
        nend=nb(j)+nd+ns;

        while nb(j)+nd+ns < length(e);
           nstart=nb(j)+nd;
           nend=nstart+ns;
           [a,nmax]=max(e(nstart:nend));
           j=j+1;
           nb(j)=nmax+nstart-1;
        end

        % plot results
        n=1:length(e);
        figure;
        plot(n,e,nb,e(nb),'ro');
        axis tight

        %% ensemble average
        Nb=length(nb);              % the number of strides detected
        nperiod=mean(diff(nb));     % find the average gait period
        nint=round(1.2*nperiod);    % chose a gait cycle interval slightly longer than nperiod
        pens=zeros(Nb-1,nint);
        for n=1:Nb-1
           pens(n,:)=e(nb(n):nb(n)+nint-1,1);
        end
        pensavg=mean(pens);     % ensemble average
        penssd=std(pens);       %    and standard deviation

        % figure, grid on, hold on;
        % plot(tens,pens');
        % plot(tens,pensavg,'k',tens,pensavg+penssd,'k:',tens,pensavg-penssd,'k:','LineWidth',2);
        % axis tight;
        % ylabel 'P-Pd';
        % xlabel 't (s)';
        % title 'ensemble average pressure'
        % figure, grid on, hold on;
        % plot(tens,uens');
        % plot(tens,uensavg,'k',tens,uensavg+uenssd,'k:',tens,uensavg-uenssd,'k:','LineWidth',2);
        % axis tight;
        % ylabel 'U';
        % xlabel 't (s)';
        % title 'ensemble average velocity'
```

```
figure
for n=1:Nb-1
plot(pens(n,:))
hold on
end

figure
plot(pensavg(1,:))

%% Loop Knee Data

%% DesiredGaitEnsemble.m
%
% Your gait data is in e
% ns=sampling frequency % nd distance from the first peak
b=LoopTorque(1:35000,end);
fs=1000;
fd=500;
ff = 1; % LOC of first peak
% find 1st peak
% a=amplitude
% nmax= index corresponding to maximum peak
[a,fmax]=max(b(1:fs));
k=1;
fb=[];
fb(k)=fmax;
% find rest of the peaks
fend=fb(k)+fd+fs;
while fb(k)+fd+fs < length(b);
   fstart=fb(k)+fd;
   fend=fstart+fs;
   [a,fmax]=max(b(fstart:fend));
   k=k+1;
   fb(k)=fmax+fstart-1;
end
% plot results
f=1:length(b);
figure;
plot(f,b,fb,b(fb),'ro');
axis tight

%% ensemble average
Fb=length(fb);              % the number of strides detected
fperiod=mean(diff(fb));     % find the average gait period
fint=round(1.2*fperiod);    % chose a gait cycle interval slightly longer than nperiod
fens=zeros(Fb-1,fint);
for f=1:Fb-1
   fens(f,:)=b(fb(f):fb(f)+fint-1,1);
end
fensavg=mean(fens);     % ensemble average
fenssd=std(fens);       %    and standard deviation

figure
for f=1:Fb-1
plot(fens(f,:))
hold on
end

figure
```

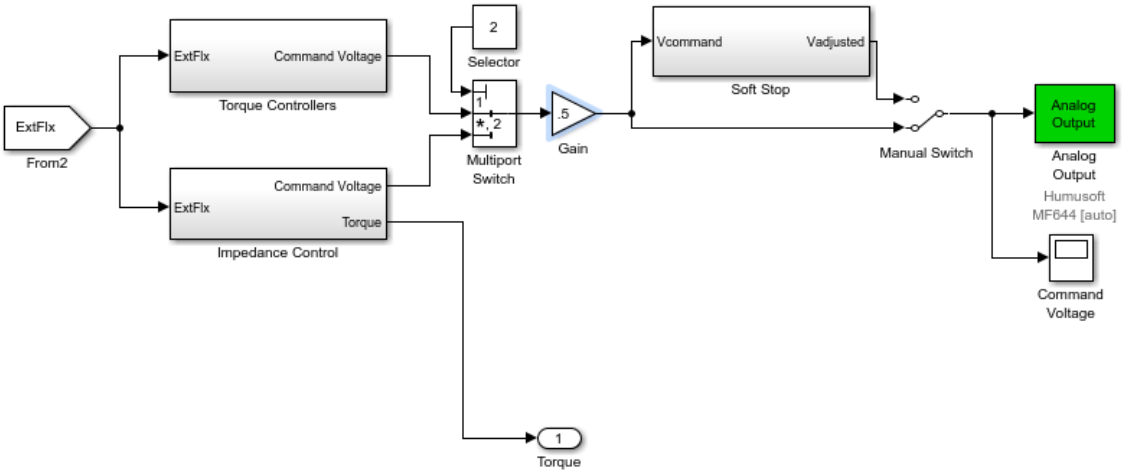
```
plot(fensavg(1,:))


figure
subplot(2,1,1)
plot(fensavg(1,250:end))
subplot(2,1,2)
plot(pensavg(1,250:end))
```

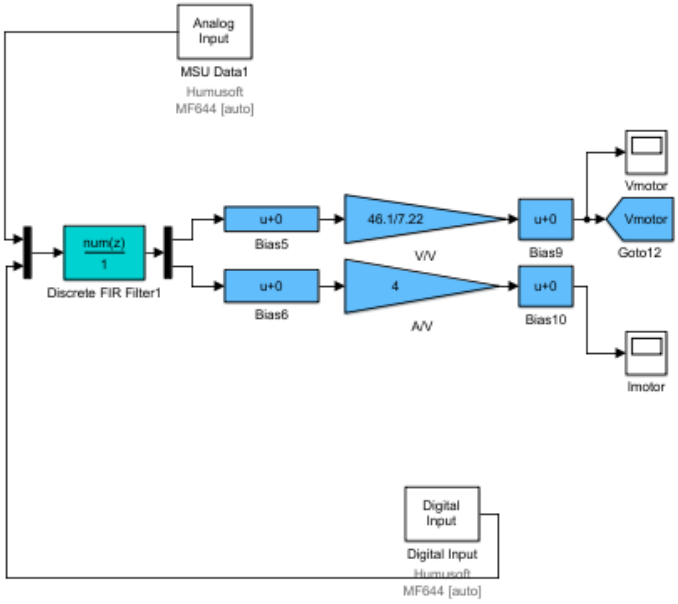
C. Simulink Models

1. Model Overview

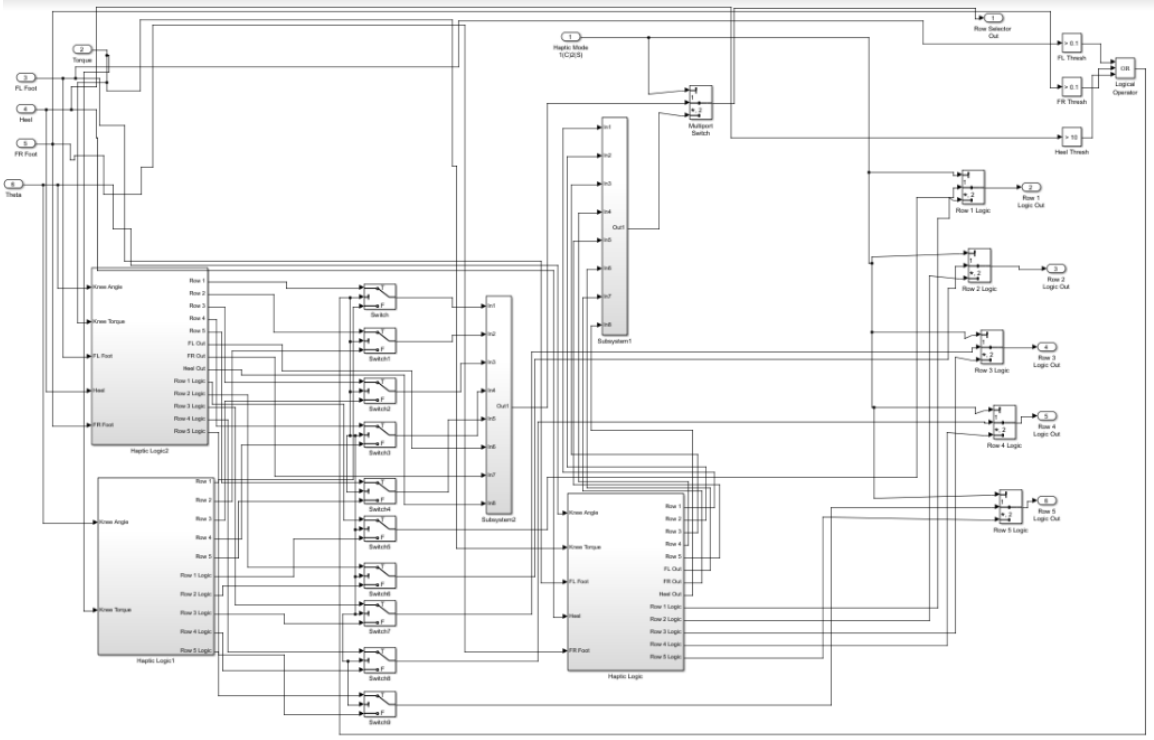


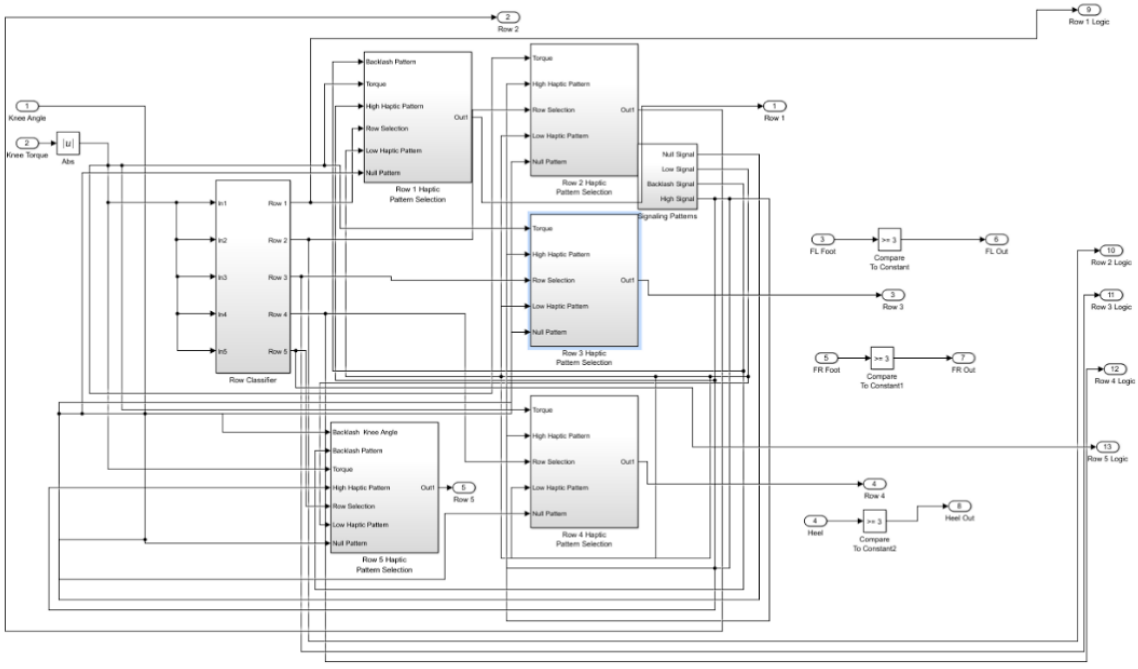
2. Limb Control





3. Haptic Control (brief)





D. IRB Documents

1. IRB # 13-34

APPROVED
MAY 16 2014
IRB # 14-34

CLARKSON UNIVERSITY
INSTITUTIONAL REVIEW BOARD

TO: Kevin Fite & Joel Canino
FROM: Johndan Johnson-Eilola, Chair of Clarkson University Institutional Review Board
RE: Institutional Review Board Approval for Human Subjects Research
DATE: May 16, 2014

Project Title: "The Synergistic use of Haptic Feedback and EMG in Lower Limb Prosthesis Control"
Approval Number: 14-34
Approved Until: May 15, 2015
Review: Expedited Review

The Clarkson University Institutional Review Board (IRB) has reviewed and approved the research protocol noted above. Please include this approval number on the cover sheet of the final, approved version of your proposal; this version needs to be signed by all researchers and the department chair (for faculty research) or advisor (for student research). Send the signed cover sheet to Rebecca Thatcher at the Division of Research PO Box 5630. The signed cover sheet affirms that you as principal investigators (PI) for this project, assume the following responsibilities:

PI Responsibilities: All researchers and research assistants in contact with human subjects or with data obtained from the involvement of human subjects should be trained in human subjects research. The on-line course required of Clarkson researchers is recommended. Primary Investigators for any IRB-approved research proposal (or faculty advisors, when Primary Investigators are students), are responsible for ensuring that all students and/or research assistants follow appropriate ethical procedures regarding human subjects research.

Data and Consent Forms: Any data or consent documentation that is considered confidential should be kept secure. This usually means it is in a locked cabinet or drawer and in password-protected computers.

Continuing Review: Since IRB approval extends for only one year from the approval date, this approval extends only through May 15, 2015. If human subjects research is to continue after that, you will need to request an extension using the Continuation Request form, even if the proposal was a multiple-year project.

This Continuation Request must be reviewed and approved prior to the expiration of the original approval. Submit your Continuation Request a minimum of one week before a regularly scheduled IRB meeting.

Protocol Modifications: Procedural changes or amendments must be submitted to the IRB using the Project Modification Request, and no changes may be made without IRB approval except to eliminate immediate hazards to subjects.

Adverse Events: You are required to immediately inform the IRB in the case of any adverse events, including exposure to risk, involving human subjects or their data.

Audit: The IRB audits selected research proposals to ensure that ethical procedures and the approved protocol are being followed. If your proposal is audited, you are required to comply with audit requests.

If you have any questions about your IRB approval or responsibilities, feel free to contact the IRB at irb@clarkson.edu or 268-6475 or Johndan Johnson-Eilola at johndan@clarkson.edu or 268-6488.

Clarkson University IRB has Federal Wide Assurance # FWA00000471- IRB00001285

Sincerely,
Johndan Johnson-Eilola (ICFT)
Johndan Johnson-Eilola
IRB Chair

cc: File

Johndan Johnson-Eilola • Chair, Institutional Review Board • 315-268-6488 • johndan@clarkson.edu
IRB Members: Leslie Russek, Robert Dowman, Sandra Harris, Ed Sachs, Alasdair Turnbull, Sheila McCarthy, Mario Cioni
Division of Research, Clarkson University • P.O. Box 5630 • Potsdam, NY 13699-5630 • Phone 315-268-4342 • Fax 315-268-6515

CLARKSON UNIVERSITY

INFORMATION REQUIRED FOR APPROVAL OF RESEARCH WITH HUMAN SUBJECTS

Please submit an electronic version of this form by emailing it to the IRB at irb@clarkson.edu . Please include all attachments, forms, and advertisements within the one proposal file as clearly labeled appendices. **Your full protocol must arrive in the Division of Research by noon, at least two weeks prior to the meeting at which you'd like it to be reviewed**. Meeting dates are posted on our web site and announced to the campus each term.

When all required revisions have been completed, you will receive an IRB approval number. Once you have this approval number, submit one signed copy of the cover sheet (page 2 of this form) to Rebecca Thatcher, the IRB Administrative Assistant, at PO Box 5630. (Signed copies should not be sent to the Chair of the IRB).

Guidelines for completing this IRB proposal form are available on the Clarkson IRB web page. If you have questions about this form or procedures, contact the IRB at irb@clarkson.edu.

Please complete the first page of this cover sheet when you first submit your proposal. Complete the bottom half after the proposal has been fully approved and you have received an IRB approval number.

Name of Investigator Kevin Fite

Name of Investigator Joel Canino

(add lines for additional Investigators)

Advisor (for student research):_____

For students: Has your advisor read this version of the proposal and approved it for submission?

___Yes ___No

Name of department, campus mailing address, and e-mail address for primary contact and any non-Clarkson Investigators

Kevin Fite,

Department of Mechanical and Aeronautical Engineering, Box 5725

Email: kfite@clarkson.edu

Mailing address (if other than department)

Title of Research:

The Synergistic Use of Haptic Feedback and EMG in Lower Limb Prosthesis Control

Date submitted: 5/14/2014

Proposed start date: Upon approval

Expected completion date: 5/31/2015

If proposal is for external funding, list agency:

Is this research being conducted in collaboration with another institution that has a review process?

- **If so, list the other institution(s):**
- **If so, has this project been approved by the review board at that institution?**
- **If yes, please submit evidence of approval; if the proposal is undergoing review, approval by the Clarkson IRB will be contingent upon evidence of approval at other institutions.**

CLARKSON UNIVERSITY

COVER SHEET FOR IRB-APPROVED RESEARCH WITH HUMAN SUBJECTS

Complete the following information after the proposal has been fully approved by Clarkson's IRB and you have received an approval number. Return the signed, paper copy of this form directly to Rebecca Thatcher, the IRB Administrative Assistant, at PO Box 5630.

Title of Research: The Synergistic Use of Haptic Feedback and EMG in Lower Limb Prosthesis Control

IRB Approval Number: 14-34

Proposed start date: 6/1/2014

Approved Until:

Expected completion date:

The investigators and faculty advisors for this project assume the following responsibilities:

PI Responsibilities: All researcher and research assistants in contact with human subjects or with data obtained from the involvement of human subjects must be trained in human subjects research, must agree to uphold the principles of the Belmont Report and the Common Rule (described in the required training). All Primary Investigators (PI) must provide to the Division of Research certification that they have completed the on-line Human Subjects Research Certification course; PI must maintain documentation that all research assistants have completed this training. PIs for any IRB-approved research proposal (or faculty advisors, when PIs are students), are responsible for ensuring that all students and/or research assistants follow appropriate ethical procedures regarding human subjects research.

Adverse Events: You are required to immediately inform the IRB in the case of any adverse events, including exposure to risk, involving human subjects or their data. Use the Adverse Events form.

Data and Consent Forms: You should secure all identifiable data or consent documentation that is considered confidential. This usually means it is in a locked cabinet or drawer and in password-protected computers.

Protocol Modifications: You are required to submit procedural changes or amendments to this approved proposal to the IRB using the Project Modification Request; you may not make changes without IRB approval except to eliminate immediate hazards to subjects.

Continuing Review: If the research is to continue after the Approved Until date noted above, you will need to request an extension using the Continuation Request form.

Audit: The IRB audits selected research proposals to ensure that ethical procedures and the approved protocol are being followed. If your proposal is audited, you are required to comply with audit requests.

By signing, below, investigators and advisors (for student research) agree that you have read and understand the university's Policy on Research with Human Subjects, you agree to the conditions stated above, and agree to ensure that the rights and welfare of the human participants ("subjects") are protected through your implementation or supervision.

PI Name Kevin Fite **Sign** __

For student research:

Advisor: _____ **Sign** _____

For faculty research:

By signing, below, as Department Chair, you acknowledge that you have read the Research Summary for this project. This signature is only an acknowledgement that you have read the Research Summary, and not a promise to support or fund this research.

Department Chair _____ Daryush Aidun **Sign** _____

CLARKSON UNIVERSITY
HUMAN SUBJECTS RESEARCH INSTITUTIONAL REVIEW BOARD PROPOSAL

1. Research Summary (400 words or less)

The research effort described in this protocol aims to examine the efficacy of mechanical tactors in the conveyance of proprioceptive information to a prosthetic user and their effect on prosthetic limb control using residual-limb electromyogram (EMG) measurements. Though the technological advances in commercially available prosthetic designs are numerous, the ability for the prosthesis to communicate with the user – in the same way that the user communicates with the prosthesis – is not well founded. The current unilateral system where the prosthetic limb simply takes cues from various sensor inputs, leaves the user clueless as to if they're using their device properly. This becomes particularly problematic if the prosthesis is controlled with EMG input commands, as the user may unknowingly send unintended commands to the prosthesis. The ability to convey sensory input to a prosthetic user will help to further establish a proper gait and increase synchronicity between user and prosthetic, which could allow for even more advanced prosthetic designs that can better incorporate EMG command and control. The ability for a user to better comprehend how the prosthetic is functioning could also dramatically lessen the period over which an amputee must train and learn how to use the prosthetic. This protocol comprises a preliminary study with able-bodied subjects of haptic feedback and its effects on EMG control of a single degree-of-freedom (DOF) robotic knee joint.

2. Introduction

Anatomically, the body's ability to interpret mechanical stimulation is varied – dependent on multiple structures located in the skin and muscle tissues. With current haptic feedback methods, the mechano-receptors being stimulated are largely situated in the integumentary system, rather than the proprioceptive receptors located in the muscle and tendon tissues. Pacinian and Meissner corpuscles are sensitive to vibration and highly adaptive. They are most sensitive to stimulation frequencies of 250Hz and <50 hertz respectively, but due to their rapid adaptation - stop generating action potentials after prolonged stimulus. The Pacinian corpuscles can also detect pressure, but only for impulsive rather than static loads. The next two systems are Merkel Disks and Ruffini corpuscles, both of which are slowly adapting sensors. They are both sensitive to pressure and skin stretch, and they continue to generate action potentials for a prolonged period of time, even with static application of pressure. Merkel Disks are sensitive to low range frequencies of about 5-15 Hz, while Ruffini corpuscles are around <40Hz. Merkel disks respond vigorously to ramp stimulus and will continue to respond for approximately 30 minutes to a prolonged, static loading. Uniquely, Ruffini corpuscles also act as thermoreceptors.

Because one cannot non-invasively replicate the body's natural proprioceptive organs, haptic feedback systems must be utilized. Common ways that haptic feedback is conveyed include: vibrotactile, pneumatic, direct–neural, skin stretch/shear, acoustic, thermal, electric, or some combination of the aforementioned haptic stimuli. This work will shy away from the more invasive and experimental methodologies of haptic feedback, such as direct-neural, electric, thermal, and acoustic methods. The proposed study will instead focus on vibrotactile and pneumatic haptic feedback systems. The vibrotactile system will stimulate the Pacinian and Meissner corpuscles while the pneumatic haptic feedback system will stimulate the Merkel disks and Ruffini corpuscles.

Fig. 1: Delsys Trigno wireless

Haptic feedback has been shown to be an effective modality for conveying information to a prosthetic user (Fan et al 2008, Armiger et al 2013, Boone et al 2011, Step et al 2010, Chatterjee 2007, and Keehoon et al 2012). The benefits of using a haptic feedback include better power conservation of the prosthetic device, as the user will not be unnecessarily stimulating the device, or markedly improved dexterity in the case of an upper-limb prosthetic.

The effort proposed in this protocol will explore the pneumatic and vibrotactile haptic feedback systems and their effect on the interaction between users and a lower limb prosthetic device. Of particular interest is the study of the effects of the introduction

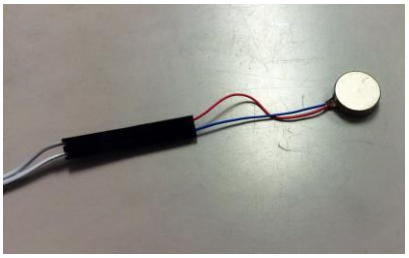


Fig. 2: Precision Microdrive motor.

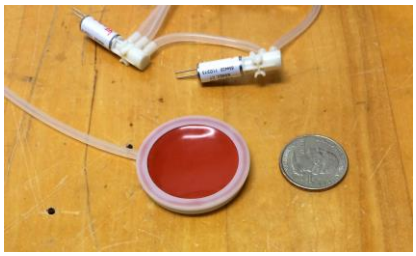


Fig. 3: Pneumatic tactor system.

of haptic feedback on EMG control for motion tracking tasks with a single-DOF prosthetic knee in a gravitation field. The EMG sensors being utilized are Delsys Trigno wireless units, shown in Figure 1. These are rechargeable EMG sensors that have a parallel bar contact system that helps to greatly mitigate noise and produce a high fidelity signal. The haptic feedback tactors being used include a set of Precision Microdrives 10mm Dura-Vibe vibrational motors, as shown in Figure 2. These motors produce a 1.4G nominal amplitude that should be more than ample to stimulate peripheral mechanoreceptors. The pneumatic haptic feedback tactors are prototypes shown in figure 3. The pneumatic tactor is a silicone membrane held by a Delrin case. As the chamber pressurizes, the silicone membrane expands and presses against the skin. The airflow to these pneumatic tactors is controlled by Lee Valves LHDA 3 port solenoid valves.

Fig. 4: Powered-knee transfemoral prosthesis.

Figure 4 shows the prototype powered-knee transfemoral prosthesis that will be used in further investigation of the congruent usage of the EMG MSUs and the haptic feedback system. Note that though a powered-knee transfemoral prosthesis will be used in the experimental evaluations, participating subjects will not be mechanically attached to the limb or use it for weight-bearing functions. Instead, control tasks will be limited to nonweight-bearing motion tracking of the bench-mounted prosthesis.

3. Objectives and Hypotheses

The objectives of this protocol are:

- Experimentally demonstrate how users characterize and react to haptic feedback.
- Experimentally explore an optimal configuration for the haptic feedback tactor arrays.
- Experimentally demonstrate user control of EMG signaling that intuitively responds to haptic feedback cues in order to follow a set gait trajectory.

The specific hypotheses to be investigated are:

- Hypothesis 1: Mechanical stimulation using pneumatic tactors will result in improved accuracy of detection and two-point discrimination, relative to stimulation with vibrational micromotors.
- Hypothesis 2: EMG control augmented with haptic feedback will provide enhanced accuracy of motion control of a single-DOF powered prosthetic knee.

Human Subjects Protection Information

4. Participants

a. Number: 10 Age range: 18-60 Gender: M&F

b. Recruitment population, including inclusion/exclusion criteria: This study will recruit participants from the Clarkson University campus community.

Inclusion criteria:

- Age between 18 and 60 years old

Exclusion criteria:

- Confounding injury or musculoskeletal problem
- Persons with a history of adhesive allergy

c. Recruitment procedures (attach advertisements or recruitment notices):

A flyer will be used on campus to promote this effort and recruit participants, please see the flyer attached in appendix A.1.

d. Incentives and compensation

There are no incentives or compensation for this research, all subjects participate on a purely voluntary basis.

e. Group assignment method

There will be no groups assigned for this study. Each participant will undergo tests with each tactor type and configuration. The order in which each subject is presented with the tactor types will be randomly determined.

5. Informed Consent

a. Procedure for obtaining Informed Consent from all participants [or their parent(s) or guardian(s)]? Describe who will obtain consent. (attach Informed Consent form)

The principal investigator will obtain informed consent from each participant. The informed consent process for locally recruited subjects will occur in the office of the Principal Investigator, Dr. Kevin Fite, and informed consent will be obtained by the PI. See attached Informed Consent Form in Appendix A.2.

b. If minors or other participants unable to provide legal informed consent are involved, outline procedures to be used in obtaining their agreement (assent) to participate, in addition to the consent of the parent(s) or guardian(s). (attach assent form or statement).

N/A

6. Study Design and Methods

a. Procedure for data collection and intervention, including duration of subject involvement:

Phase One

This study will compare haptic feedback with pneumatic tactors and vibrational motors. Evaluations will be performed to assess single-point detection and two-point discrimination. The full battery of tests for each individual will require a single two-hour session. Assignment of order of tactor presentation will be randomized.

1. The randomized tactor set will be affixed in a random spacing determined by the tactor type. Tactors will be held in place using medical grade silicone sheets. The sheets will provide sufficient adherence to each participant's skin to hold the tactors stationary. For both types of tactors, they will be placed on the subject's dominant side, along a line parallel to the subject's spine, with the top-most location being just below the sub-inferior angle of the scapula. Both tactor types will be arranged in one of multiple inter-tactor spacings.

2. After the tactors are affixed to the subject, each tactor will be sequentially assigned a number and manually actuated multiple times and for the subject. The subject will be asked if they wish to go through this actuation process again until they state that they are comfortable with the tactor positioning and numbering convention.

3. A Matlab program will randomly actuate a single tactor and sustain that actuation until the subject selects which tactor they believe is being actuated on the GUI provided by the program. The Matlab program will then have a 5 second cessation period before actuating the next tactor. This cycle will continue for a total set of 30 actuations. This user input data and the actual generated sequence data will be stored by Matlab.

4. Another Matlab script will then randomly actuate either a single tactor or a pair of them in a similar manner to section 3. The subject will be prompted to answer, via GUI, whether one or two tactors are being actuated, but they are not required to specify which two tactors are being actuated. This will be recorded in the same way as section 3.

5. The tests from section 3 and 4 will be done two more times, with the same tactor type, but each time in a different tactor-array configuration.

6. Upon completion of these tests, the subject will have the tactors removed and be given a break if they so desire. After the subject is ready to resume, the second type of tactor will be used and steps 1-5 will be repeated.

Phase Two

This component will study EMG control of a robotic joint with and without haptic feedback. Each subject will participate in approximately eight two-hour sessions (assuming the subject completes the

study). Participants for this phase of the study may include subjects from Phase One, but participation in the Phase Two study is not limited to those individuals. The subjects will receive training and testing with a random set of haptic feedback tactors (either pneumatic or vibrotactile). The type of haptic feedback used will also be randomly determined to be either an error-based haptic feedback system or a haptic feedback based on the current state of the prosthetic limb. The error based haptic feedback system will actuate the tactors in an effort to correct the user's use of their muscles - to move the prosthetic position to the desired trajectory position. Because this error-based system is corrective in nature, it minimizes the overall amount of haptic stimulus felt by the user. The current state haptic feedback system actuates the haptic feedback tactors continually based on the position of prosthetic, having nothing to do with course correction signaling. To clarify this randomization process, the possible combinations of tactors and haptic feedback methods is listed in the table below.

Configuration	Tactor Type	Feedback Style
1	Vibrotactile	Error Based
2	Vibrotactile	Current State
3	Pneumatic	Error Based
4	Pneumatic	Current State

1. The tactors selected will be affixed to the subject's body in the optimum way established by phase one. Tactors will be held in place using medical grade silicone sheets. The sheets will provide sufficient adherence to each participant's skin to hold the tactors stationary. Two Delsys EMG sensors will be affixed to the area of their dominant leg corresponding to the quadriceps and hamstring. Preliminary electrode locations will be determined based on clinical standards (Perotto 2005). Manual palpation will be used to more precisely narrow down EMG placement. Prior to electrode attachment, each site will be wiped with isopropyl alcohol.

The subject will then have their dominant leg immobilized in a seated position. The powered knee transfemoral prosthetic will be mounted on a platform lateral to the subject's, now immobilized, dominant leg. With the prosthetic mounted in such a way, the subject will be able to see the leg actively flex and extend as they modulate their EMG signaling. The subject will be asked to perform a series of isometric knee extensions between 0% and 100% of maximum voluntary contraction for a 30-second period. This procedure will then be repeated for isometric knee flexions. This initialization routine will establish the range of muscle contractions in each direction and any co-contraction that may occur due to inability to isolate individual muscles. This information will be used to determine a normalized mapping between measured EMG and control parameters of the prosthetic limb.

2. The first training all subjects will undergo is a simple position test tutorial. The subject will be shown a screen, on this screen will be a visualization of the leg's current position and the desired position of the leg. Using only the visual representation, the subject will need to - through the use of EMG signaling - control the current position as best they can to match the desired position. This desired position will be changing to a new position as the subject successfully moves the powered limb to the correct position. This will continue for a few desired positions and the data will be recorded and archived by the Matlab program used to simulate this training tutorial. This whole training tutorial will be done as many times as is necessary for the subject to feel comfortable with the EMG control interface.

3. The subject will then go through a set of training tests, with or without haptic feedback. These training tests will be very similar to the actual testing that the subject will undergo at a later time. The subject will be looking at a screen, which will display the desired position of the limb and its actual positioning. The subject will then need to, through the use of EMG signaling, move the limb into the desired rest position. Once the subject has successfully moved the limb into the desired rest position they must continue to change the position of the limb as the desired position transitions along a band-limited, pseudo-random trajectory, one minute in duration. The user's trajectory as well as the Matlab trajectory will be recorded. The subject will go through a series of 8 of these randomly determined training tests, 4 with haptic feedback, 4 without.

4. The following session, the subject will then undergo the actual testing. The testing procedure will be very similar to that described in the training tests presented in step 3, but with some key differences. The possible configurations that the subject can go through will include variation in end-point mass affixed to the limb. Though the subject will be able to see the limb, the weight added will be kept unknown to the subject. This will be done by removing the weighted bag, leaving the patients field of view, changing the weight if necessary, and then returning and placing the weight back on the ankle of the limb. There will also be randomness as to whether or not the subject gets feedback during the test. Each of these possible configurations will be tested twice, for a total of 16 tests that the patient will undergo. The table provided below helps to clarify the possible configurations.

Configuration	**Added Weight**	**With or Without Haptic Feedback**
1	No Weight	With Feedback
2	No Weight	Without Feedback
3	2 lb	With Feedback
4	2 lb	Without Feedback
5	4 lb	With Feedback
6	4 lb	Without Feedback
7	6 lb	With Feedback
8	6 lb	Without Feedback

5. In the next session, the subject will then be set up again as in step 1, with a random tactor and haptic feedback combination that has not yet been used.

6. The subject will then undergo the training and testing for this new combination as described in steps 2 through 4.

7. Steps 5 and 6 will be repeated for the remainder of combinations, culminating in a total of 8, two-hour sessions between the training and testing required for each combination of tactor and haptic feedback.

b. Measurement tools (attach questionnaires and surveys):

Data will be collected in the phase one study through the Matlab program. Data collection for the second phase will be done using a Matlab program which will store its own generated data as well as the data from the Delsys EMGs.

c. Equipment interfacing with subjects:

1. All subjects will have direct contact with the haptic feedback tactors, both the pneumatic tactor and the vibrational motors. These will be affixed to the subject using medical grade slicone sheets that provide adequate adherence to both the tactors and the subject's skin. Tactors are reusable and will be sterilized after each use by wiping down with 70% isopropyl alcohol swabs. The silicone sheets are reusable and will be washed with a mild detergent after each use.

2. For the Phase 2 evaluations, each subject will be instrumented with a pair wireless EMG electrodes (Delsys Trigno™ Wireless EMG System). These electrodes will be secured with double-sided tape. Electrodes are resusable and will be sterilized after each use by wiping down with 70% isopropyl alcohol pads.

3. For the Phase 2 evaluations, subjects will be placed in a purpose built chair that will be used to immobilize one of their legs with Velcro straps. This is done to ensure that the hamstring and quadriceps muscles targeted for EMG control are contracted isometrically.

4. A laptop PC (Lenovo T500, Microsoft Windows XP Professional v2002, Intel 2.66Hz) will be used for data collection and real-time control of the benchtop prosthesis. Data acquisition and control is handled with the following hardware and software:

a. NI DAQCard-6036E, 16-Bit, 200 kS/s E Series Multifunction DAQ

b. Matlab v7.7, Simulink v7.2, Real-Time Windows Target v3.2, Real-time Workshop v7.2, Real-Time Workshop embedded Coder v5.2,

d. If deception is necessary, justify and describe debriefing procedures (attach debriefing statement):

N/A

e. Analysis of outcomes:

For the data collected in phase one, linear regression will be used, likely ANOVA. This will be done to compare the different configurations of tactors in an effort to find if there is one significantly superior configuration for each tactor type. Similarly, for the analysis of phase two data, a linear regression will be done once more for the sets of test data. This analysis will look at analyzing what significant contribution haptic feedback has on the EMG controlled, powered, lower limb prosthetic. It will also work to determine if the style of feedback implemented is also of significance.

7. Risks and Benefits

a. Risks: detail stress, physical, psychological, social or economic harm that may be incurred by participation in this research? Describe risks (including risks associated with release of personal information) and methods for minimizing these risks.

There are no invasive procedures associated with this protocol. The physical risk of being immobilized in the seat apparatus will also be greatly mitigated by having a quick release buckle system on the straps, so in the case of unforeseen emergency, the subject will be able to quickly become un-restrained.

Participants who suffer from claustrophobia may also suffer from undue stress from the immobilization of the leg in phase two. This will be explained to the subject prior to experimentation. If subjects experience discomfort with being restrained, they can withdraw from the study at any point.

The concern of adhesive allergy, which is very rare, will be greatly mitigated by the exclusion criteria provided above. It is very rare that a person will have an undiscovered adhesive allergy at the age range of subjects for this test. Patch tests will be conducted prior to initiating the tests to ensure subjects are not allergic to the EMG electrode adhesive or the silicone sheets used to secure the tactors. These tests will entail attaching the adhesive tape and silicone to locations on each subject's arm and monitoring the site for allergic reaction over a 5-minute period.

b. Address how subjects will be monitored for adverse effects and what remediation is offered.

The subjects will be monitored and asked how they feel throughout the tests. This is in an additional effort to detect any allergic reactions (to the adhesive used to secure the EMG electrodes or silicone used to secure the tactors) and also to remediate any discomfort the subject may encounter. Every time the tactors or electrodes are removed, the skin will be examined for any hive, rash, or blister formation, which would lead to immediate discontinuation of the study.

If an adverse event requiring medical attention does occur during participation in this study, the investigators will contact Clarkson Campus Safety to report the need for medical assistance. Campus Safety will then determine the appropriate actions to take.

c. Does the data to be collected relate to illegal activities? If so explain

N/A

d. Rate risk level. Check the most appropriate risk level below. (Minimal risk means that the probability and magnitude of harm or discomfort anticipated in the research are not greater in and of themselves than those ordinarily encountered in daily life or during the performance of routine physical or psychological examinations or tests.)

☒ The research involves no more than minimal risk to subjects.

☐ The research involves more than minimal risk to subjects but the risk(s) represents a minor increase over minimal risk, **or**

☐ The research involves more than minimal risk to subjects and the risk(s) represents more than a minor increase over minimal risk.

e. Methods for providing anonymity or confidentiality. If audio or video tapes are used, when will they be erased? For research involving patients, describe how HIPAA requirements will be met.

The coding for data collected will use an alphanumeric tag that identifies sex, race, and age of the subject followed by a three-digit number. Any other information that could be used to identify a particular subject using the alphanumeric tag will be stored in a locked safe in the PI's office. The names and personal information of participating subjects will not be made publicly available without the express written consent of the participating subject. Personal identifying information will not be included in any research publications or presentations that result from this study. Video and other data will be digitally archived on password protected computers to which only researchers associated with this study will have access. The video will be erased from the camera as soon as the data is transferred to the password protected computer. In general, subjects will be recognizable in the archived video. Thus, the investigators will obtain written consent from the participating subject prior to public release of such video. Should the subject object to public release of the video, he or she can opt to not provide such consent while continuing to participate in the study.

f. Plan for destroying private, identifiable data at the end of the research project.

The only private identifiable data will be the hardcopy table that links each subject with their assigned alphanumeric tag. This table will be removed from the PI's locked safe and shredded upon termination of the study. The PI Fite will be responsible for ensuring that such data is properly destroyed.

g. Benefits to participants:

The primary objective of the proposed effort is to support the development of lower-limb prosthesis technology for amputees. The target participants of this study will be non-amputees, thus this study will likely have little to no immediate impact on their life.

h. Benefits to society from the research:

The potential benefits of this research are considerable for the lower-limb amputee population. To date, there is no commercial system that can utilize EMG sensors and haptic feedback synergistically. The results of this study may lead to a means for amputee patients to experience higher quality prosthesis function and, thus, to reduce the negative consequences of poor function. The potential risks are low and the potential benefits to amputees and society are notable.

i. Rate benefit level. A research benefit is considered to be something of health-related, psychosocial, or other value to an individual research subject, or something that will contribute to the acquisition of generalizable knowledge. Money or other compensation for participation in research is not considered to be a benefit, but rather compensation for research-related inconveniences. Check the most appropriate benefit level, below:

☒ No prospect of direct benefit to individual subjects, but likely to yield generalizable knowledge about a population group to which the subject belongs;

☐ No prospect of direct benefit to individual subjects, but likely to yield generalizable knowledge that may benefit a population group to which the subject belongs; or

☐ The research involves the prospect of direct benefit to participating subjects.

8. Investigational Device Exemption (IDE): Does this research involve any device that has not been FDA approved or which is being used for a purpose for which it has not been approved? If so, please review Clarkson's guidelines regarding IDE. What are the results of safety testing performed for this device?

N/A

9. Conflict of interest statement:

The Clarkson University researchers have no conflict of interest with regard to any technological developments that may result from this study.

10. Citations

Armiger, Robert S., Francesco V. Tenore, Kapil D. Katyal, Matthew S. Johannes, Alexander Makhlin, Mandy L. Natter, J. Edward Colgate, Sliman J. Bensmaia, and R. Jacob Vogelstein. "Enabling Closed-Loop Control of the Modular Prosthetic Limb Through Haptic Feedback." *Johns Hopkins APL Technical Digest*. 31.4 (2013): 345-353.

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Chatterjee, Aniruddha, Vikram Aggarwal, Ander Ramos, Soumyadipta Acharya and Nitish V Thakor. "A brain-computer interface with vibrotactile biofeedback for haptic information." *Journal of NeuroEngineering and Rehabilitation* 4 (2007): 40.

Fan, Richard E., Martin O. Culjat, C-H. King, Miguel L. Franco, Richard Boryk, James W. Bisley, Erik Dutson, and Warren S. Grundfest. "A Haptic Feedback System for Lower-Limb Prostheses." *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* 16.3 (2008): 270-277.

Kim, Keehoon, and JEdward Colgate. "Haptic feedback enhances grip force control of sEMG-controlled prosthetic hands in targeted reinnervation amputees." *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* 20.6 (2012): 798-805.

Perotto, Aldo O.. *Anatomical Guide for the Electromyographer*. 4th ed. Springfield, IL: Charles C Thomas, 2005.

Stepp, Cara E., and Yoky Matsuoka. "Relative to direct haptic feedback, remote vibrotactile feedback improves but slows object manipulation." *Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE*, (2010).

A.1 Recruitment Flyer

Participants Needed!

Researchers in the Mechanical and Aeronautical Engineering department at Clarkson University need participants for a research experiment related to sensory feedback using mechanical vibratory stimulation for improved control of a prosthetic leg.

In order to volunteer for this study, participants must be:

- Between the ages of 18 and 60.
- Have no previous history of allergic reaction to adhesives.

Each session will last approximately two hours. Each participant may participate in as many as nine of these sessions, but study participation does not require all nine sessions to be completed.

Are there benefits to participating? Participants will NOT be compensated for their participation in this study, but you will be greatly helping to advance our work!

For more information, please contact:

Dr. Kevin Fite: kfite@clarkson.edu

- OR -

Joel Canino: caninojm@clarkson.edu

A.2 Informed Consent Form

Clarkson University
Documentation of Informed Consent to Participate in Research

Project Title: The Use of Haptic Feedback Synergistically with EMG Sensors
Researcher(s): **Kevin Fite, Ph.D., Joel Canino**

Institutional Review Board (IRB) approval number: 14-34 **Approval valid until**: May 15, 2015

You have been asked to be a part of the research described here. Participation is voluntary.

The purpose of this study: This study will investigate the effects of sensory feedback using mechanical vibratory stimulation on the willful control of a prosthetic leg.

What to expect:
The first phase of this study will require only one session, the second phase of this study will require eight sessions, each lasting approximately two hours. The first visit should not exceed two hours and is for informing you of your rights if you consent to participate in the study and testing.

For the first phase of testing you will be hooked up to different vibratory feedback tactors and asked to identify which tactor is on. This will be repeated for a total of 6 tests with different tactors and configurations.

The second phase of this study will be spanned across eight, two hour sessions, there will be a training session followed by a testing session, for a total of four training sessions and four testing sessions. During the training sessions you will have EMG sensors as well as the tactors from phase one attached to you. You will be trained to control the EMG signal that your muscles will be outputting in an effort to control a powered prosthetic leg. This will be done with and without vibratory feedback. After this training session, the next session will be testing. The tests conducted will be very similar to what was done during training, just with more variations and more tests performed.

If you have any questions about this research, you may contact the principal investigator, Kevin Fite (ph: 315-268-3809, email: kfite@clarkson.edu)

Risks and discomforts to you if you take part in this study:

There are no invasive procedures associated with your involvement in this study.

Your leg will be immobilized during the second phase of the study. If you are claustrophobic, or uncomfortable with having your leg immobilized, please feel free to discuss this with the principal investigator.

The medical adhesive and silicone sheets being used can very rarely cause an allergic reaction in people who have adhesive allergies. If you have a history of adhesive allergy, please let the investigator know. Over the course of the study, the skin under and surrounding the adhesive and silicone will be constantly monitored for any signs of allergic reaction.

If an adverse event requiring medical attention does occur during participation in this study, the investigators will contact Clarkson Campus Safety to report the need for medical assistance. Campus Safety will then determine the appropriate actions to take.

The benefits to you if you take part in this study:

The results of this study are not expected to be of direct benefit to you, but the knowledge gained may ultimately be of benefit to individuals with lower-limb amputations.

What will you receive for taking part in this study:

There is no compensation for taking part in this study. Participation is voluntary.

What will happen to the information collected in this study:

The information collected will be kept confidential as much as is permitted by law. Public release of your name or other identifying information will only occur with your express consent. Data collected from the session will only be released in the public domain (via publication in research journals or educational presentations to students or at conferences) after 7 days have passed. Should you choose to withdraw from this study within this 7-day window, your data will not be made public and will be deleted from the laboratory database. Should you withdraw after the 7-day window, your data will still be kept confidential provided that it has not already been publicly released.

Digital video may be taken of you during testing. This video may contain full-body shots in which you may be recognizable to viewers. Select **Yes** or **No** at the bottom of the page to indicate whether you permit the public release of your video data. Such public release will largely be limited to research or educational presentations associated with this study. You are not required to provide this consent in order to participate in the study. Without such consent, the investigators will not publicly release any of the video associated with your participation.

What rights do you have when you take part in this study:

Participation in this research is voluntary. Deciding not to take part, or to stop being a part of this research will result in no penalty, fine or loss of benefits which you otherwise have a right to. If you have questions about your rights as a research subject or if you wish to report any harm, injury, risk or other concern, please contact Dr. Johndan Johnson-Eilola, Associate Chair of the Clarkson University Institutional Review Board (IRB) for human subjects research: (315)268-6488 or Johndan@clarkson.edu

Conflict of Interest: The Clarkson University researchers have no conflict of interest with regard to any technological developments that may result from this study.

Informed Consent: Please sign here to show you have had the purpose of this research explained and you have been informed of what to expect and your rights. You should have all your questions answered to your satisfaction. Your signature shows that you agree to take part in this research. You will be given a copy of this consent form to keep for your records**.**

Yes, you can use my video:_____ No, do not reveal my video data:_____

Subject Name (Printed): _____ Subject Number: _____

Signature of volunteer: _____ Date: _____

Signature of researcher
obtaining informed consent: _____ Date: _____

2. IRB # 18-04

Clarkson University

Documentation of Informed Consent to Participate in Research

Project Title: The Use of Haptic Feedback Synergistically with EMG Sensors

Researcher(s): Kevin Fite, Ph.D and Joel Canino

Institutional Review Board (IRB) approval number: 18-04 **Approval valid until**: July 31, 2018

You have been asked to be a part of the research described here. Participation is voluntary.

The purpose of this study: This study will investigate the effects of sensory feedback using mechanical vibratory stimulation on the willful control of a prosthetic leg.

What to expect:

The first phase of this study will require only one session, the second phase of this study will require eight sessions, each lasting approximately two hours. The first visit should not exceed two hours and is for informing you of your rights if you consent to participate in the study and testing.

For the first phase of testing you will be hooked up to different vibratory feedback tactors and asked to identify which tactor is on. This will be repeated for a total of 6 tests with different tactors and configurations.

The second phase of this study will be spanned across eight, two hour sessions, there will be a training session followed by a testing session, for a total of four training sessions and four testing sessions. During the training sessions you will have EMG sensors as well as the tactors from phase one attached to you. You will be trained to control the EMG signal that your muscles will be outputting in an effort to control a powered prosthetic leg. This will be done with and without vibratory feedback. After this training session, the next session will be testing. The tests conducted will be very similar to what was done during training, just with more variations and more tests performed.

If you have any questions about this research, you may contact the principal investigators, Kevin Fite (ph: 315-268-3809, email: kfite@clarkson.edu) or Joel Canino (ph: 860-993-2527, email: caninojm@clarkson.edu)

Risks and discomforts to you if you take part in this study:

There are no invasive procedures associated with your involvement in this study.

Your leg will be immobilized during the second phase of the study. If you are claustrophobic, or uncomfortable with having your leg immobilized, please feel free to discuss this with the principal investigator.

The medical adhesive and silicone sheets being used can very rarely cause an allergic reaction in people who have adhesive allergies. If you have a history of adhesive allergy, please let the investigator know. Over the course of the study, the skin under and surrounding the adhesive and silicone will be constantly monitored for any signs of allergic reaction.

If an adverse event requiring medical attention does occur during participation in this study, the investigators will contact Clarkson Campus Safety to report the need for medical assistance. Campus Safety will then determine the appropriate actions to take.

The benefits to you if you take part in this study:

The results of this study are not expected to be of direct benefit to you, but the knowledge gained may ultimately be of benefit to individuals with lower-limb amputations.

What will you receive for taking part in this study:

There is no compensation for taking part in this study. Participation is voluntary.

What will happen to the information collected in this study:

The information collected will be kept confidential as much as is permitted by law. Public release of your name or other identifying information will only occur with your express consent. Data collected from the session will only be released in the public domain (via publication in research journals or educational presentations to students or at conferences) after 7 days have passed. Should you choose to withdraw from this study within this 7-day window, your data will not be made public and will be deleted from the laboratory database. Should you withdraw after the 7-day window, your data will still be kept confidential provided that it has not already been publicly released.

Digital video may be taken of you during testing. This video may contain full-body shots in which you may be recognizable to viewers. Select **Yes** or **No** at the bottom of the page to indicate whether you permit the public release of your video data. Such public release will largely be limited to research or educational presentations associated with this study. You are not required to provide this consent in order to participate in the study. Without such consent, the investigators will not publicly release any of the video associated with your participation.

What rights do you have when you take part in this study:

Participation in this research is voluntary. Deciding not to take part, or to stop being a part of this research will result in no penalty, fine or loss of benefits which you otherwise have a right to. If you have questions about your rights as a research subject or if you wish to report any harm, injury, risk or other concern, please contact Dr. Johndan Johnson-Eilola, Associate Chair of the Clarkson University Institutional Review Board (IRB) for human subjects research: (315)268-6488 or Johndan@clarkson.edu

Conflict of Interest: The Clarkson University researchers have no conflict of interest with regard to any technological developments that may result from this study.

Informed Consent: Please sign here to show you have had the purpose of this research explained and you have been informed of what to expect and your rights. You should have all your questions answered to your satisfaction. Your signature shows that you agree to take part in this research. You will be given a copy of this consent form to keep for your records**.**

Yes, you can use my video:_____ No, do not reveal my video data:_____

Subject Name (Printed): _____ Subject Number: _____

Signature of volunteer: _____ **Date:** _____

Signature of researcher

obtaining informed consent: _____ **Date:** _____

3. IRB # 17-40

APPROVED
JUN 02 2017
IRB # 17-40

CLARKSON UNIVERSITY
INSTITUTIONAL REVIEW BOARD

To:	Kevin Fite/Joel Canino
From:	Johndan Johnson-Eilola, Chair of Clarkson University Institutional Review Board
Subject:	Institutional Review Board Approval for Human Subjects Research
Date:	June 2, 2017
Project Title:	"The Use of Haptic Feedback to Enhance User Perception of an EMG-Controlled Transfemoral Prosthesis"
Approval Number:	17-40
Approval Expires:	June 1, 2018
Initial Review:	☒ Full Committee Review or ☐ Expedited Review, Category 1

The Clarkson University Institutional Review Board (IRB) has reviewed and approved the research protocol noted above. In the case of expedited reviews, the IRB must document the category under which the review was completed (contact the IRB for a detailed explanation of expedited review categories). Include the IRB approval number on the cover sheet of the final, approved version of your proposal; this version needs to be signed by all researchers and the department chair (for faculty research) or advisor (for student research). Send the signed cover sheet to Rebecca Thatcher at the Division of Research PO Box 5630. The signed cover sheet affirms that you as principal investigators (PI) for this project, assume the following responsibilities:

PI Responsibilities: All researchers and research assistants in contact with human subjects or with data obtained from the involvement of human subjects should be trained in human subjects research. Specific IRB training procedures are available from the IRB. Primary Investigators for any IRB-approved research proposal (or faculty advisors, when Primary Investigators are students) are responsible for ensuring that all students and/or research assistants follow appropriate ethical procedures regarding human subjects research.

Data and Consent Forms: Any data or consent documentation that is considered confidential should be kept secure. This usually means it is in a locked cabinet or drawer and in password-protected computers.

Continuing Review: Since IRB approval extends for only one year from the approval date, **your project's approval extends only through June 1, 2018.** If human subjects research is to continue after that, you will need to request an extension using the Continuation Request form, even if the proposal was a multiple-year project.

This Continuation Request must be reviewed and approved prior to the expiration of the original approval. Submit your Continuation Request a minimum of one week before a regularly scheduled IRB meeting.

Protocol Modifications: Procedural changes or amendments must be submitted to the IRB using the Project Modification Request, and no changes may be made without IRB approval except to eliminate immediate hazards to subjects.

Adverse Events: You are required to immediately inform the IRB in the case of any adverse events, including exposure to risk, involving human subjects or their data.

Audit: The IRB audits selected research proposals to ensure that ethical procedures and the approved protocol are being followed. If your proposal is audited, you are required to comply with audit requests.

If you have any questions about your IRB approval or responsibilities, feel free to contact the IRB at irb@clarkson.edu or 268-6475 or Johndan Johnson-Eilola at johndan@clarkson.edu or 268-6488.

Clarkson University IRB has Federal Wide Assurance # FWA00000471- IRB00001285.

Sincerely,

Johndan Johnson-Eilola/IRB Designee
IRB Chair/IRB Designee

cc: File

Johndan Johnson-Eilola • Chair, Institutional Review Board • 315-268-6488 • johndan@clarkson.edu
IRB Members: Leslie Russek, Robert Dowman, Sandra Harris, Kay DePerno, Loren Nowak
Division of Research, Clarkson University • P.O. Box 5630 • Potsdam, NY 13699-5630 • Phone 315-268-4342 • Fax 315-268-6515

CLARKSON UNIVERSITY

INFORMATION REQUIRED FOR APPROVAL OF RESEARCH WITH HUMAN SUBJECTS

Instructions

Please submit an electronic version of this form by emailing it to the IRB at irb@clarkson.edu . Please include all attachments, forms, advertisements within the one proposal file as clearly labeled appendices. Your full protocol must arrive in the Division of Research by noon, at least one week prior to the meeting at which you'd like it to be reviewed. Meeting dates are posted on our web site and announced to the campus each term. *When all required revisions have been completed, you will receive an IRB approval number;* once you have this approval number, submit one signed copy of the cover sheet (page 2 of this form) to Rebecca Thatcher, the IRB Administrative Assistant, at PO Box 5630 (*Please note that signed copies should not be sent to the Chair of the IRB*). Guidelines for completing this IRB proposal form are available on the Clarkson IRB web page. If you have questions about this form or procedures, contact at IRB at irb@clarkson.edu.

Please complete the first page of this cover sheet when you first submit your proposal. Complete the bottom half after the proposal has been fully approved and you have received an IRB approval number.

Name of Investigator Kevin Fite

Name of Investigator Joel Canino

(add lines for additional Investigators)

Advisor (for student research):_____

For students: Has your advisor read this version of the proposal and approved it for submission?

_x_ Yes ___No

Name of department, campus mailing address, and e-mail address for primary contact and any non-Clarkson Investigators

Kevin Fite, Department of Mechanical and Aeronautical Engineering, Box 5725

Email: kfite@clarkson.edu

Mailing address (if other than department)

Title of Research:

The Use of Haptic Feedback to Enhance User Perception of an EMG-Controlled Transfemoral Prosthesis

Date submitted:

Proposed start date: May 1, 2017

Expected completion date: April 30, 2018

If proposal is for external funding: N/A **Agency**: N/A

Is this research being conducted in collaboration with another institution that has a review process?

- **If so, list the other institution(s):**

- **If so, has this project been approved by the review board at that institution?**

- **If yes, please submit evidence of approval; if the proposal is undergoing review, approval by the Clarkson IRB will be contingent upon evidence of approval at other institutions.**

CLARKSON UNIVERSITY

COVER SHEET FOR IRB-APPROVED RESEARCH WITH HUMAN SUBJECTS

Complete the following information after the proposal has been fully approved by Clarkson's IRB and you have received an approval number. Return the signed, paper copy of this form directly to Rebecca Thatcher, the IRB Administrative Assistant, at PO Box 5630.

Title of Research: The Use of Haptic Feedback to Enhance User Perception of an EMG-Controlled Transfemoral Prosthesis

IRB Approval Number:

Proposed start date: May 1, 2017

Approved Until: April 30, 2018

Expected completion date: April 30, 2018

The investigators and faculty advisors for this project assume the following responsibilities:

PI Responsibilities: All researcher and research assistants in contact with human subjects or with data obtained from the involvement of human subjects must be trained in human subjects research, must agree to uphold the principles of the Belmont Report and the Common Rule (described in the required training). All Primary Investigators (PI) must provide to the Division of Research certification that they have completed the on-line Human Subjects Research Certification course; PI must maintain documentation that all research assistants have completed this training. PIs for any IRB-approved research proposal (or faculty advisors, when PIs are students), are responsible for ensuring that all students and/or research assistants follow appropriate ethical procedures regarding human subjects research.

Adverse Events: You are required to immediately inform the IRB in the case of any adverse events, including exposure to risk, involving human subjects or their data. Use the Adverse Events form.

Data and Consent Forms: You should secure all identifiable data or consent documentation that is considered confidential. This usually means it is in a locked cabinet or drawer and in password-protected computers.

Protocol Modifications: You are required to submit procedural changes or amendments to this approved proposal to the IRB using the Project Modification Request; you may not make changes without IRB approval except to eliminate immediate hazards to subjects.

Continuing Review: If the research is to continue after the Approved Until date noted above, you will need to request an extension using the Continuation Request form.

Audit: The IRB audits selected research proposals to ensure that ethical procedures and the approved protocol are being followed. If your proposal is audited, you are required to comply with audit requests.

By signing, below, investigators and advisors (for student research) agree that you have read and understand the university's Policy on Research with Human Subjects, you agree to the conditions stated above, and agree to ensure that the rights and welfare of the human participants ("subjects") are protected through your implementation or supervision.

PI Name Kevin Fite **Sign**

PI Name Joel Canino **Sign**

For student research:

Advisor: _____ **Sign** _____

For faculty research:

By signing, below, as Department Chair, you acknowledge that you have read the Research Summary for this project. This signature is only an acknowledgement that you have read the Research Summary, and not a promise to support or fund this research.

Department Chair _____ Daniel Valentine **Sign** _____

CLARKSON UNIVERSITY

HUMAN SUBJECTS RESEARCH INSTITUTIONAL REVIEW BOARD PROPOSAL

1. Research Summary (400 words or less)

Prior research conducted by the Investigators (Clarkson University IRB# 14-34) sought to incorporate haptic feedback into one-degree of freedom motion tracking tasks with prosthetic knee system. These tasks involved a powered transfemoral prosthesis controlled using electromyogram measurements from antagonist muscle pairs. Able-bodied subjects were tasked with following stepwise and sinusoidal trajectories with and without haptic feedback and visual feedback. These tests successfully demonstrated that haptic feedback offers a significant improvement in motion tracking while deprived of visual feedback, paving the way for the use of haptic feedback as a training tool for improved EMG-control of powered limb systems.

This research is now focused on experimentally evaluating an improved, higher-dimension haptic feedback array for weight-bearing functions with the powered prosthetic knee system. Three possible haptic stimulation schemes will be investigated: one where spatial information is the only information communicated, one where only torque information is communicated, and one that is a combination where the torque and spatial schemes are used during different phases of gait.

The objective of this study is to evaluate the efficacy of a higher-dimensional tactile feedback array in EMG-based control of a powered-knee prosthesis for locomotor functions. The study will recruit participants with unilateral transfemoral amputation. Participants will initially be tasked with performing nonweight-bearing functions (in order to gain proficiency with EMG-control and tactile haptic feedback), followed by weight-bearing functions to include standing, level-ground walking, ramp ascent/descent, and stair ascent/descent. Data to be collected and analyzed will include (1) EMG measurements from antagonist muscles in the residual thigh, (2) angle and torque of the prosthetic knee, and (3) pressure measurements of the prosthetic-side foot during foot-ground interaction. The investigators will also solicit qualitative feedback from each participant via a survey to be administered following completion of testing. It is hypothesized that the incorporation of a high-dimensional haptic feedback array and stimulation scheme will allow for a substantial and meaningful improvement in prosthetic-limb perception beneficial to EMG-control during weight-bearing locomotor functions.

2. Introduction

Prior work in EMG-based limb control

The prototype EMG-controlled transfemoral prosthesis, shown in Figure 1, was developed and investigated by Hoover et al. (2012) and Dawley et al. (2013), under Clarkson University IRB #'s 10-38 and 11-27.

Figure 1: Transfemoral prosthetic leg used for this investigation (Hoover, 2012).

The limb possesses a rotary potentiometer at the knee joint, an axial force transducer at the actuator-joint interface, and pneumatic pressure sensors at the heel and ball of the carbon fiber composite prosthetic foot (Otto Bock Journey 1E44). The knee is actuated by a linear actuator consisting of a brushed DC motor (Maxon RE40) and a ballscrew assembly (Nook ECS-10020-RA). The system is powered by custom fabricated lithium polymer battery packs, which supply a combined 48v at 2,000 mAh (12 lithium polymer cells) (Hoover, 2012).

Using a working foundation for the controls as provided by Dawley et al, the powered-knee prosthetic limb is controlled through a modulation of effective limb stiffness as a function of EMG from two antagonist thigh muscle groups. That is to say, this system enables EMG control of knee impedance (Dawley, 2013). A principal component analysis (PCA) is performed on initialization data which is collected under different muscle contraction states including isometric flexion contractions, isometric extension contractions, muscles at rest. The PCA calibration handles co-contraction levels exhibited by hamstrings and quadriceps and generates a manifold that maps normalized extensor and flexor contraction magnitudes to the desired stiffness and equilibrium angle of the prosthetic knee.

The commanded effective knee stiffness for the powered knee is dependent on the input signals u_e and u_f, which correspond to the normalized magnitudes of extensor and flexor EMG. Desired knee stiffness is given by:

$$K = K_{max}\sqrt{u_e^2 + u_f^2} \tag{1}$$

where K_{max} is a constant that corresponds to the maximum achievable stiffness of the prosthetic knee. As seen in eq. (1), the commanded stiffness is an algebraic function of the magnitude of the two inputs. The normalized EMG inputs are also used to command a desired angular rate of change (ω_d) for the knee, which is a piecewise linear function of the ratio of u_f to u_e. From this desired angular velocity of the knee, a desired angular position can be computed through numerical integration as follows:

$$\theta_d = \int \omega_d dt \tag{2}$$

Using eqs. (1) and (2), the resultant desired knee torque is then given by:

$$\tau_d = K(\theta_d - \theta) - B\omega \tag{3}$$

Where θ is the instantaneous position of the leg, ω is the instantaneous angular velocity of the leg, and B is the effective viscous damping about the knee. This control architecture enables both nonweight-bearing and weight-bearing control and is thus effective for locomotor and non-locomotor functions (Dawley, 2013).

The in-situ investigation of the prosthetic limb and EMG-based impedance control architecture was conducted by Dawley et al. This investigation involved a single transfemoral amputee subject, who was subjected to varying locomotor tasks including stair ascent/descent and level-ground walking. Overall performance was found to be good, similar to that of current state of the art (SOA) limb technology, but there were some noted issues. The user of the limb would command large hyper-extensive knee moments when entering the stance phase of gait. It was proposed that this hyper-extension is a defensive habit, ensuring that the limb does not collapse during stance phase. This defensive technique is not required however, and leads to mechanical fatigue of the limb as well as increased power consumption. It was proposed that this over-torquing of the knee was due to a combined lack of perceptual awareness for the prosthesis and rehabilitative training that encourages more defensive gait techniques, particularly when using a passive limb.

Prior work of others in haptic feedback

It was proposed in prior research that haptic feedback could be an effective means of ameliorating the perceptual deficit observed in the use of the EMG-controlled powered knee prosthesis. Haptic feedback is classically defined as a system that “touches” the body in an effort to convey some form of information. This has since expanded into any system that artificially induces some form of sensory stimulus. These systems include vibrating motors, elastic pressure vessels, skin stretch apparatuses, surface skin electrodes, direct neural integration, and many more less common devices. The system most often encountered are vibrating motors, which provide vibrotactile feedback, ideally in the 250-300Hz range or the 50-60Hz range, which are the desired frequencies for specific mechanoreceptive organs (Purves, 2001). These stimulus frequency ranges and desired vibratory motor

specifications were extensively tested and rated based on the quality of feedback perception by Hanif et al. (Hanif, 2013).

The most common commercial implementation of haptic feedback technology is in the communication and entertainment industry. Haptic feedback has proven to be an effective method of alerting cell phone users and creating a more immersive environment for virtual reality and video games. While these systems work to provide a tertiary perceptual awareness, in the prosthetic limb industry it has become an interesting prospect to use haptic feedback as a way of restoring some semblance of limb awareness. This haptic feedback implementation has been extensively explored in powered upper limb technologies. Many researchers have investigated haptic feedback as a methodology to enhance upper limb grasp tasks and to provide object texture information. A smaller subset of these researchers investigated the incorporation of haptic feedback in patients that have received targeted reinnervation (TR) therapy (Bensmaia, 2014). Targeted reinnervation is the process where a select muscle group is surgically denervated. In the upper limb case, these targeted muscles include select groups of the pectoral and serratus muscles. The ulnar, median, musculocutaneous, and distal radial nerves are then cut at their distal ends and surgically transplanted into the previously denervated muscle tissue. While this work was initially conducted in an effort to enhance sEMG interfacing and allow for a more intuitive control experience for upper limb amputees, Kuiken et al. noticed that some subjects could actually perceive some perceptual abstraction of their severed limb (Kuiken, 2007A). Kuiken et al. continued to investigate this phenomenon which has now led to the modernization of TR techniques that purposely reconstruct the lost limb's perceptual mapping (Kuiken, 2007B; Herbert, 2016).

Brown et al. tested subjects using an EMG controlled gripper, which they enhanced with vibrotactile and force-feedback. These researchers found that the combination of vibrotactile and force feedback allowed for greater grip management and perception of slip (Brown, 2013). Brown et al. later created an EMG-controlled powered manipulator for use in able-bodied individuals. This system was enhanced with joint-force feedback and vibrotactile feedback. They again found that force-feedback is an effective way of inciting proper magnitudes of grip forces (Brown, 2015). Christiansen et al. tested an EMG-controlled grasping task while using haptic feedback in the presence and absence of visual feedback. They found that the incorporation of haptic feedback showed significant improvement in controls when deprived of visual feedback. The haptic feedback also enhanced the user-perceived performance of the grasp tasks when provided visual feedback (Christiansen, 2013). Aziziaghdam et al. applied haptic feedback to the clavicle in an effort to provide material stiffness characteristics. These test subjects were able to successfully distinguish a sense of softness and hardness of items that they could not see and accurately rate them from softest to hardest (Aziziaghdam, 2014). Treadway et al. used an EMG-controlled manipulator which was subjected to a random antagonistic driving signal. The error signal was conveyed via a pressure haptic feedback cuff. Haptic feedback allowed the users to effectively manage a steady state, despite the antagonistic signaling (Treadway, 2015). Van der Riet et al. sought to create a low-cost prosthetic hand that could rival current SOA models. They found that the inclusion of haptic feedback greatly enhanced the functionality of their economical hand design, which totaled less than $1,000 (Van der Riet, 2015). Behbahani et al. experimented with the use of haptic feedback as an object-shape communication system. With this haptic feedback schema, these researchers successfully demonstrated that users were able to explore and accurately identify objects with a manipulator while being deprived of visual feedback (Behbahani, 2015).

Kim et al. experimented on amputees that had undergone TR therapy, seeking to investigate how multiple haptic feedback devices could affect the EMG control of a powered upper limb prosthesis with a specific focus on grasping. Kim et al.'s work importantly uncovered that there are limitations to the discernible complexity of haptic feedback inputs, wherein their subjects could not discern simultaneous shear and pressure sensation (Kim, 2012). Gibson et al. investigated the use of auditory feedback in TR patients as a means of avoiding perceptual deficits caused by neuropathy, with an improvement in

performance observed (Gibson, 2015). Rombokas et al. used vibrotactile feedback on TR patients to improve performance in the manipulation of virtual objects via force-motion tasks (Rombokas, 2013). Herbert et al. used intraoperative somatosensory evoked potentials on individual fascicles of the median and ulnar nerves to target specific sensory fascicles that – when rerouted – would allow for targeted percutaneous haptic stimulation of a reconstructed hand map in a transhumeral amputee. This TR therapy led to the successful restoration of haptic perception of the individuals hand and enhanced EMG control of dexterous tasks (Herbert, 2014).

In the lower limb environment, few researchers have explored the use of haptic feedback to provide kinesthetic feedback. Fortin et al developed an event-based methodology for conveying vibratory characteristics of foot-ground interactions in an effort to convey high resolution terrain information to lower limb amputees. Their test subjects were able to accurately discern multiple surfaces and characteristic features; they are currently working on a high resolution prosthetic-skin interface (Fortin, 2014). Fan et al. investigated the use of silicone bladders to convey foot-ground interactions to the users of a passive transtibial prosthetic limb. They found that this system could reliably convey kinesthetic information (Fan, 2008).

Prior work of the investigators in haptic feedback

The discoveries and conjecture that came from prior investigations of haptic-prosthetic interfacing then led to the investigation of integrating haptic feedback into the control of the powered transfemoral prosthetic initially investigated by Hoover et al. and Dawley et al. (Hoover, 2012; Dawley 2013). The haptic feedback arrays shown in Figure 2 were designed for this testing. One array consisted of an aluminum pressure vessel with three chambers that could be pressurized via three Lee Valves LHDA242321 solenoid valves. When these chambers are pressurized, a silicone membrane covering an orifice expanded into the skin interface, imparting a pressure sensation. The second array was 3D printed using ABS where three Precision Microdrives PicoVibe 12mm vibrating motors were suspended in silicone-filled sockets.

Figure 2: (Left) Quasi-static pressure feedback array. (Right) Vibrotactile array.

These two haptic feedback arrays were used to help subjects navigate a non-weight bearing single-degree of freedom stepwise motion tracking task. These tasks were conducted with and without visual feedback, and with and without haptic feedback. The haptic feedback system would tell the user to flex (proximal tactor), extend (distal tactor) or remain within a nominally tuned error-band (middle tactor). During the control test, subjects had a knee goniometer affixed to their sound limb and they were tasked with following the desired trajectory, yielding the best expected performance for the subject. The results of these initial tests showed that quasi-static pressure haptic feedback significantly improved the control of the powered transfemoral prosthetic, particularly when deprived of visual feedback (Canino, 2016A).

This success motivated further refinement of the haptic feedback control architecture in an effort to successfully convey more sophisticated motion trajectories. Subsequent testing by Canino et al.

(2016B) investigated the non-weight bearing motion tracking of these sinusoidal trajectories with and without visual feedback and haptic feedback. The haptic feedback scheme for this testing transitioned between three possible states. The first state would communicate a pace-making signal, wherein the proximal most tactor described a peak region, the middle tactor described an ascent or descent region, and the distal most tactor described a trough region of the signal. The other two states worked to communicate user error by providing an ascending or descending sequential pattern at a distinctly different frequency (higher in the case of a low-frequency trajectory, slower in the case of a high-frequency trajectory), implying that the user needed to flex or extend the limb respectively. This testing led to the discovery that the haptic feedback system could still offer significant performance improvements with respect to frequency content but not amplitude content, when deprived of visual feedback (Canino, 2016B).

The inability for the system to successfully convey desired knee angle magnitude content and frequency content simultaneously was largely a limitation of the haptic feedback system used. The haptic feedback arrays only had three tactors – and therefore were lacking in spatial resolution. Interestingly, the inclusion of visual feedback yielded markedly larger variance in performance than when visual feedback was removed. This detrimental effect that visual feedback had on the tracking of a rhythmic motion has been well documented as a psychophysical phenomenon, wherein active focus on rhythmic tasks often leads to detrimental over and under performance by the user. Ankarali et al. at Johns Hopkins also observed this kind of error with a haptic feedback enhanced ping-pong paddle juggling task. They found that haptic feedback in the absence of visual feedback enhanced the rhythmic performance of the user significantly over visual feedback alone. They propose that such a system has better rhythmic stability because there is a reduction in the cycle to cycle variability that would occur with visual perception and any coinciding attempts to over-correct perceived instability in the system (Ankarali, 2016).

Results from Canino et al. also suggest that the implementation of corrective haptic feedback could be used to train proper locomotor techniques vis-a-vis forced motion tracking. That is to say, such a haptic feedback apparatus could provide a gait pacing for the user to follow, similar to the error feedback system featured in the motion tracking tasks. Instead of prompting a subject to follow some arbitrarily generated motion trajectory, one could program the system to coax the user into following a scalable, real-time gait trajectory. It is hypothesized that this could greatly reduce the rehabilitation process while also dissuading the formation of improper gait habits (Canino, 2016C). To further reinforce this hypothesis, McKinney et al. demonstrated that patients with peripheral neuropathy were able to make significant compensatory gait adjustments with the assistance of haptic feedback. These significant improvements were observed with minimal training and resulted in an increase in step speed, better step cadence, step length, and peak joint power (McKinney, 2014).

The prior haptic feedback designs were never intended to be the final product, they were bulky and designed strictly for their intended experimentation. It was desirable to develop a haptic feedback design that could allow for greater spatial resolution through the implementation of more tactors, as well as greatly reduced weight and profile. The basis of this design was featured around a 3x5 grid of vibratory motors with a triangular array of redesigned pneumatic pistons at the proximal-most area of the vibrotactile grid, as shown in Figure 3. The design of this grid was further informed by work done by Novich et al., who demonstrated necessary spacing dimensions for independent perception when using vibrating motors (~ 6 cm), and proper usage of spatiotemporal sweeping for enhanced resolution and perception in closer spacing (Novich, 2015).

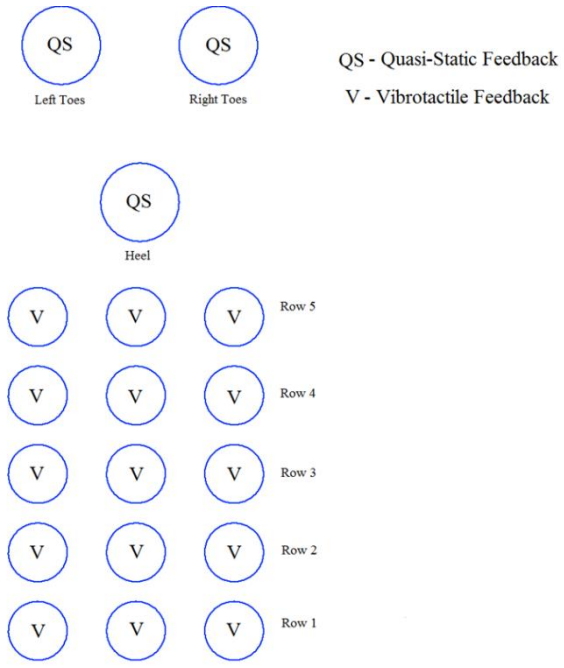

Figure 3: Preliminary tactor arrangement.

This system will allow for greater spatial resolution and increased flexibility in the communicative capabilities. The current plan will be to use the 5 rows of sensors to convey one of three possible communication schemes. The first scheme works to convey knee angle information i.e. rows 1 through 5 represent knee angle ranges of (90- 73), (84- 50), (62– 28), (40 – 6), and (17 – 0) degrees respectively. These ranges were determined by dividing up the possible range of knee angles into five overlapping fields with a band-size of 34 degrees. This field size was chosen based on pilot testing. The terminal 90 and 0 degrees will be expressed by a rhythmic pulsation of the appropriate terminal row tactors. Should the user attempt to drive the knee beyond the range of mechanical motion, in flexion or extension, a strong pulsatile “warning feedback” will be imparted. If the knee is left in a state of rest, the stimulation will decrease to a state of rest in an effort to prevent over-stimulation and desensitization. The overlap presented in row activation, combined with pulsatile stimulation at the hyper extension and flexion regions, takes the 5 distinct rows and expands their spatial resolution into 11 distinct combinatorial regions. Figure 4 shows this excitation pattern and distinct regions better. The rows each contain 3 vibrating motors, which can be used to convey magnitude of EMG-commanded where 1 active tactor indicates low torque and 3 active tactors (the full row stimulated) indicates high torque.

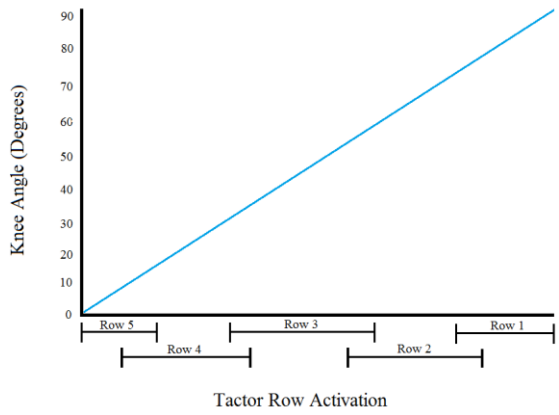

Figure 4: Plot of knee angle versus vibrotactile row activation.

The second possible scheme is based on communicating limb-torque information. In this scheme, row 3 will function as the central row dividing the field into two directions, flexion and extension torque. As torque is applied, the corresponding directional field (rows 3-5 or rows 3-1) will have a proportional amount of tactors activated, with the stimulus pattern extending outward from row 3 (see Figure 5). As the torque approaches an established limit, all of the tactors in the directional field will be actuated and the system will begin to impart an increasing frequency and magnitude pulsatile feedback rhythm. This will culminate into a strong pulsatile "warning feedback," when the subject drives the limb to the torque limit. This type of error feedback will also be presented if the user has driven the limb to its mechanical limits (hyper extension or flexion), but it will be distinct from the high-torque warning in that only row 5 or row 1 will be actuated. Note that this system does not convey knee-angle state information outside of warnings when the limb has reached its mechanical limits. In rhythmic processes like gait, it may be sufficient (or better) to just provide limb torque information as it is simpler and possibly more intuitive.

Figure 5: Torque-dominant model examples in the extension direction with the top row showing torque within a normal range (green-yellow-red color transition used to show increasing torque intensity) while the bottom row shows how torque approaching the torque limit will lead to an increase in the number of tactors pulsing (identified by jagged edges around the tactor).

The third possible scheme is a combination of the prior two schemes. The spatial-dominant scheme will be used to describe the swing phase of gait (or any motion wherein ground interactions are not observed) while the torque-dominant scheme will be used to convey torque information during the stance phase. As seen in Figure 6, the torque-dominant scheme is selected in the phase of gait for which knee torque varies over its largest range (0-60%-stride), whereas the spatial-dominant scheme is selected in the phase of gait where knee angle exhibits its largest variation (60-100%-stride). The transition between the two schemes will be dictated by foot-ground sensor information. When heel strike is initiated, the system will transition into the torque-dominant scheme. This is intuitive as the limb is essentially anchored by foot-ground interactions, meaning that the user doesn't need to worry about the limb's spatial orientation and can instead focus on torque information. Once the foot leaves the ground (toe-off) the system will transition back into a spatially-dominant scheme that conveys knee angle information. It is proposed that this bi-modal scheme will offer the best performance benefits.

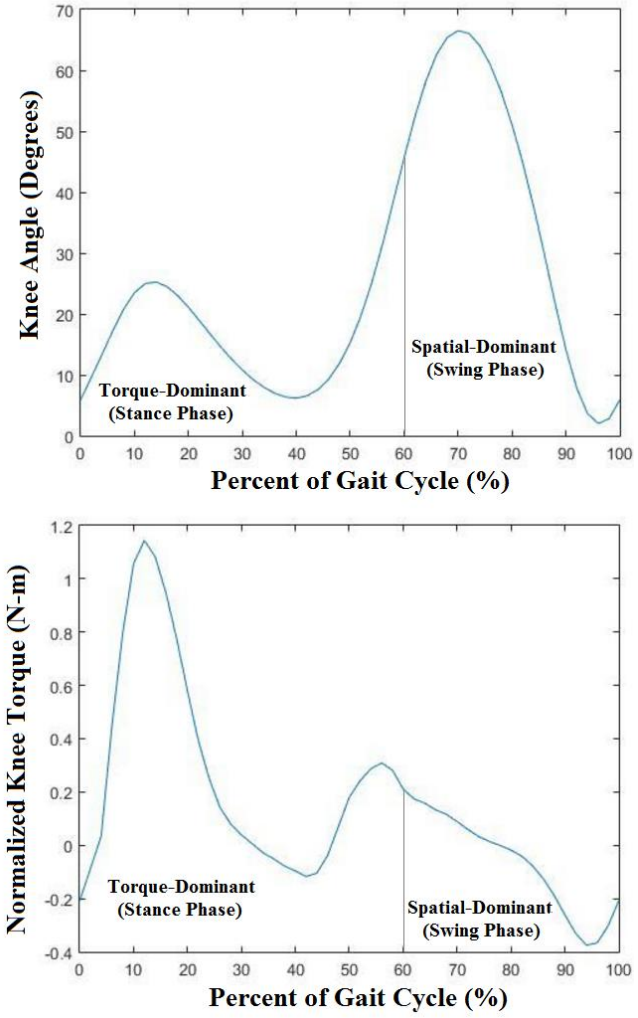

Figure 6: Graph showing combined haptic feedback scheme and transition between torque and spatial dominant schemes throughout the gait cycle.

No matter which scheme is chosen, the three triangularly arranged pneumatic pistons will convey foot-ground interactions. The two pistons arranged in a row will convey left and right field toe contacts

while the one piston below them will convey heel strike and heel contact during stance (Figure 9). The use of multiple modalities of haptic feedback, and the benefits it can provide, have been demonstrated extensively in the literature. Researchers Pamungkas et al., Jimenez et al., Walker et al., and Ajoudani et al. all utilized multiple modes of haptic feedback in an effort to communicate multiple sets of information including pressure for a range of grip forces and vibration for a range surface sensations. These researchers found that the inclusion of multiple modes of haptic feedback greatly increased the amount of information that could effectively be communicated (Ajoudani, 2014; Jimenez, 2014; Pamungkas, 2015; Walker, 2015).

Multiple arrays have been produced using 3D-printing techniques with a material called NinjaFlex, a printable elastomer that easily conforms to the surface topology of the subject's limb (Figure 13). This haptic feedback system is currently being designed for the anterior forearm and will be held in place by an adjustable bracing system.

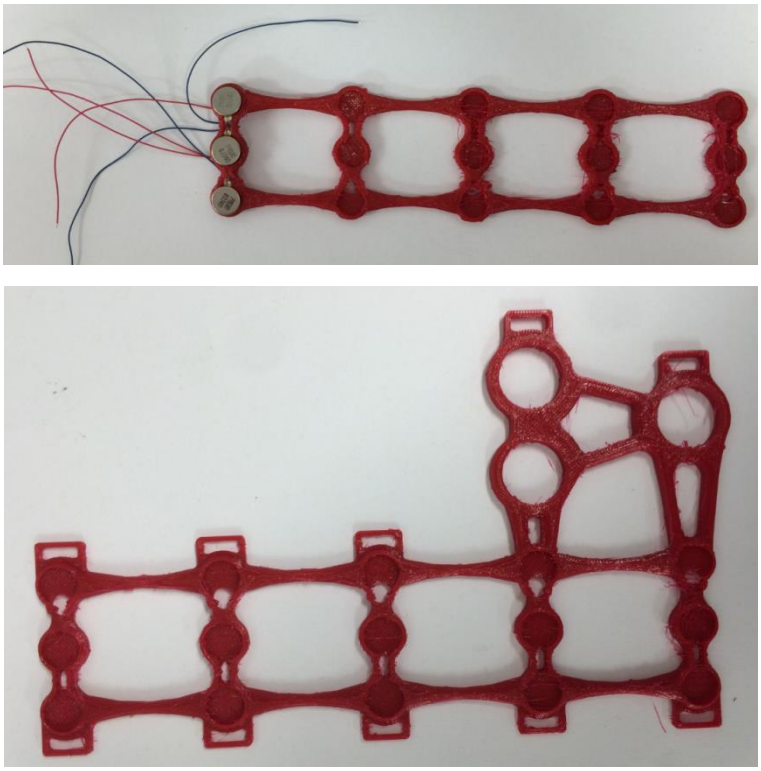

Figure 13: Prototype tactor sockets additive manufactured using NinjaFlex.

3. Objectives and Hypotheses

The Hypotheses of this protocol are:

- The inclusion of haptic feedback will help enhance user-prosthesis interactions, allowing for a more immersive prosthetic experience and marked improvements in performance.

The objectives of this protocol are:

- Demonstrate the efficacy of the haptic feedback communication methodology via gait trajectory tracking tasks.

- Demonstrate enhanced gait performance with the incorporation of haptic feedback in the weight-bearing EMG control of a powered transfemoral prosthesis.

Human Subjects Protection Information

4. Participants

a. Number: 10 Age range: 18-60 Gender: M&F

b. Recruitment population, including inclusion/exclusion criteria:

Inclusion criteria:

- Age between 18 and 60 years old
- Unilateral transfemoral amputation
- Currently fit with a definitive prosthesis
- Able to ambulate unassisted with prosthesis
- In possession of an available definitive and/or backup socket compatible with the powered prosthetic knee prototype

Exclusion criteria:

- Confounding injury or musculoskeletal problem
- Weight ≥ 200 lb

c. Recruitment procedures (attach advertisements or recruitment notices):

A flyer will be used on campus to promote this effort and recruit participants. See the flyer attached in Appendix A.1. Additionally, subjects will be recruited by contacting persons who have previously stated an interest in participating or participated in research trials conducted by the investigators. Potential participants who appear to meet the study criteria will be mailed or emailed a cover letter (see Appendix A.2) and consent documents (see Appendix A.3). The subject will be followed up via phone by the Principal Investigator to verify they received the cover letter and consent document. At this time, the researchers will determine if the individual is interested in participating in the study, answer their questions, ensure they comprehend the study and verify that they meet the inclusion/exclusion criteria. If the potential subject is interested in participation, an appointment will be made thereafter for consenting and testing at Clarkson University.

d. Incentives and compensation

There are no incentives or compensation for this research, all subjects will participate on a purely voluntary basis.

e. Group assignment method

There will be no groups assigned for this study.

5. Informed Consent

a. Procedure for obtaining Informed Consent from all participants [or their parent(s) or guardian(s)]? Describe who will obtain consent. (attach Informed Consent form)

The principal investigator will obtain informed consent from each participant. The informed consent process for recruited subjects will occur in the offices of the Principal Investigators, Dr. Kevin Fite and Joel Canino, and informed consent will be obtained by the PI. See attached Informed Consent Form in Appendix A.3.

b. If minors or other participants unable to provide legal informed consent are involved, outline procedures to be used in obtaining their agreement (assent) to participate, in addition to the consent of the parent(s) or guardian(s). (attach assent form or statement).

N/A

6. Study Design and Methods

a. Procedure for data collection and intervention, including duration of subject involvement:

Testing will be conducted on at least one transfemoral amputee subject. This testing will require multiple days: a few preliminary days of training wherein the subject will don the prosthetic limb and practice with the limb and haptic feedback schemes, and three days of testing, each devoted to one of the feedback schemes. Trial days will begin with a brief training exercise and transition into the subject using the prosthetic limb in the traversing of level ground, stair ascent, stair descent, ramp ascent, and ramp descent. All of these trials will be conducted repetitively, with and without one of the haptic feedback schemes. To clarify, each day will focus on a single haptic feedback scheme, and the days with which a particular scheme is used will be randomized. During the testing process, an experienced clinician, Dr. Christopher Towler, will also be present. This clinician will offer valuable insight into gait observations as well as ensuring proper prosthetic fit, functionality, and subject safety. The clinician will observe the subject's proficiency with their personal prosthetic limb before testing to validate the subject's inclusion in the trial, and observe the subject's use of the EMG-controlled powered transfemoral prosthesis to ensure that the subject's safety is not compromised during the course of the trial. Any compromise of subject safety will lead to immediate discontinuation of testing and re-evaluation of the subject's continued

participation. In addition, each subject will also be observed with his/her definitive prosthesis after each session to ensure that use of the bionic knee system has not compromised functional abilities with the daily-use prosthesis.

Data collected will be varied and task-dependent. Depending on system-readiness, there may be gait analysis conducted using motion capture technology, particularly with level-walking. The Orthocare Compass™ system can be used to effectively extrapolate gait mechanics of the prosthetic limb in environments where motion capture is not feasible, like ramps and larger flights of stairs. Force plates will be placed at the bottom of a stair system in an effort to record the entrance and exit of stair ascent and descent, respectively. EMG, foot pressure, knee impedance, knee angle, knee torque, and knee velocity data will also be recorded through the Simulink program for all trials. Video recording outside of motion capture will also be valuable for gait quality analysis.

All of the data will be analyzed and explored with the intent of understanding how the haptic feedback system and schemes affects the prior assertions of Dawley et al, wherein hyper-extension was evident (Dawley, 2013). It will also be important to consider the perception of the test subject, so a survey will also be conducted (see Appendix A.4). This survey will inform if there was any improvement in perceived limb-quality when any of the three haptic feedback schemes were provided. If it is found that haptic feedback does not appreciably reduce the hyper-extension of the limb during stance phase, it may be important to consider that ingrained habits are responsible. It would then be suggested that the prosthetic user would train with the system in an effort to re-learn proper control habits and re-analysis can then be conducted.

The test subject will be responsible for providing a socket for implementation with the powered transfemoral prosthesis. As indicated in the Inclusion Criteria, only subjects in possession of personal sockets compatible with the powered knee prototype will be included in the study. Components to be reused among all subjects include the EMG electrodes, the haptic interface, and the prosthetic knee prototype (distal to the socket interface). The EMG electrodes and tactors of the haptic interface are cleaned with a 70% ethanol, 30% water solution after each use as per medical sanitary standards. The powered prosthetic limb is also re-used between subjects but does not require cleaning because it does not interface directly with the subject. The powered limb will be affixed to the subject's personal socket, and the length of the pylon will be adjusted to ensure symmetry between the affected-side and contralateral limbs. To do so, the overall length of the powered prosthesis prototype distal to the socket interface will be adjusted to match that of the subject's definitive prosthesis. Proper prosthetic limb sizing and alignment will be ensured by the clinician.

b. Measurement tools (attach questionnaires and surveys):

Data will be collected throughout the study through the Matlab program. The survey to be given during Study 3 is attached (see Appendix A.4).

c. Equipment interfacing with subjects:

5. Haptic feedback tactors, both the pneumatic tactors and the vibrational

motors.

6. Laptop PC: ASUS ROG G752VS-XB78K – OC Edition, Microsoft Windows 10, i7 2.7 GHz.

c. Humusoft MF644 Data Acquisition Board

d. Matlab v7.7, Simulink v7.2, Real-Time Windows Target v3.2, Real-time Workshop v7.2, Real-Time Workshop embedded Coder v5.2,

2. Powered-knee Transfemoral Prosthesis.

3. EMG electrodes: Otto Bock 13E202 EMG electrodes.

d. If deception is necessary, justify and describe debriefing procedures (attach debriefing statement):

N/A

e. Analysis of outcomes:

For the data collected, linear regression will be used on correlation data, likely ANOVA. The data analysis will show the efficacy of the three haptic feedback communication methods, allowing for statistical comparison of the different methods.

7. Risks and Benefits

a. Risks: detail stress, physical, psychological, social or economic harm that may be incurred by participation in this research? Describe risks (including risks associated with release of personal information) and methods for minimizing these risks.

There are no invasive procedures associated with this protocol. However, all participating subjects are assumed to be at risk of falling. Because of this risk, subjects will be suspended in a wheeled harness system when performing locomotor functions. Additionally, Dr. Christopher Towler, licensed physical therapists and faculty members in the Department of Physical Therapy, will oversee all gait evaluations proposed in this protocol. Their combined experience in human subjects testing, including the involvement of amputee participants, leaves them well suited to conducting the proposed data collection and ensuring the well being of the participants.

b. Address how subjects will be monitored for adverse effects and what remediation is offered.

The subject will be monitored and asked how they feel throughout the tests. Adverse effects are not expected, but in the extremely rare chance that subjects have some kind of contact dermatitis in response to one of the interfacing devices, testing will be discontinued immediately and the subject will be escorted to proper medical services, if necessary.

During training and evaluations, individual participants will be closely monitored by the clinical personnel throughout the training and data collection. If imbalance or instability is observed, the training or data collection will be temporarily halted. The clinical researchers will assess the reasons for the imbalance and, depending upon assessment, determine whether the session can continue or should be stopped altogether. In the event of a fall, the participant will be immediately evaluated for injury by the clinical personnel, and the session will be terminated. Should additional medical attention be required, the participant will be transported to the medical facility of their choice or, if appropriate, 911 will be called.

c. Does the data to be collected relate to illegal activities? If so explain

No

d. Rate risk level. Minimal risk means that the probability and magnitude of harm or discomfort anticipated in the research are not greater in and of themselves than those ordinarily encountered in daily life or during the performance of routine physical or psychological examinations or tests. Check the most appropriate risk level below:

1. ____The research involves no more than minimal risk to subjects.

2. __x___The research involves more than minimal risk to subjects but the risk(s) represents a minor increase over minimal risk, **or**

3._____ The research involves more than minimal risk to subjects and the risk(s) represents more than a minor increase over minimal risk.

e. Methods for providing anonymity or confidentiality. If audio or video tapes are used, when will they be erased? For research involving patients, describe how HIPAA requirements will be met.

With consent of the participating subject, some personally identifiable information may be publically released. This personal information will be limited to video containing images of the participant's face. Should the subject object to public release of the video, he or she can opt to not provide consent for video release while continuing to participate in the study. Video and other data will be digitally archived on password protected computers to which only researchers associated with this study will have access. The video will be erased from the camera as soon as the data is transferred to the password protected computer.

f. Benefits to participants:

The primary objective of the proposed effort is to support the development of lower-limb prosthesis technology for amputees. This study will likely have little to no immediate impact on their life as their research is contributing to ongoing technological development. But their work may help themselves, or others they know, in the future.

g. Benefits to society from the research:

The potential benefits of this research are considerable for the lower-limb amputee population. To date, there is no commercial system that can utilize EMG sensors and haptic feedback synergistically. The results of this study may lead to a means for prosthetics patients to experience higher quality prosthesis-user interfacing and, thus reduce the negative consequences of poor functional interaction. The potential risks are low and the potential benefits to amputees and society are notable.

h. Rate benefit level. A research benefit is considered to be something of health-related, psychosocial, or other value to an individual research subject, or something that will contribute to the acquisition of generalizable knowledge. Money or other compensation for participation in research is not considered to be a benefit, but rather compensation for research-related inconveniences. Check the most appropriate benefit level, below:

1. _____No prospect of direct benefit to individual subjects, but likely to yield generalizable knowledge about a population group to which the subject belongs;
2. ___X__No prospect of direct benefit to individual subjects, but likely to yield generalizable knowledge that may benefit a population group to which the subject belongs; or
3. _____The research involves the prospect of direct benefit to participating subjects.

8. Investigational Device Exemption (IDE): Does this research involve any device that has not been FDA approved or which is being used for a purpose for which it has not been approved? If so, please review Clarkson's guidelines regarding IDE. What are the results of safety testing performed for this device?

N/A

9. Conflict of interest statement:

The Clarkson University researchers have no conflict of interest with regard to any technological developments that may result from this study.

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Appendices

A.1 Recruitment Flyer for Local Participants

Participants Needed!

Researchers in the Mechanical and Aeronautical Engineering department at Clarkson University need participants for a research experiment related to the control of a powered-knee prosthesis. Participants will control a powered-knee prosthesis while being provided vibratory stimulus on their forearm that directly correlates to the function of the prosthetic limb. The research seeks to understand whether or not this vibratory stimulus improves control of the prosthesis.

In order to volunteer for this study, participants must:

- Be between the ages of 18 and 60.
- Be able and willing to stand and walk for periods of time greater than 15 minutes.
- Be willing to commit 2 to 3 hours of time per day for 8 days.
- Have a transfemoral amputation.
- Be at least 1 year post-amputation with regular prosthetic limb use.

Are there benefits to participating? Participants will NOT be compensated for their participation in this study, but you will be directly helping to advance our work!

For more information, please contact:

Dr. Kevin Fite: kfite@clarkson.edu

- OR -

Joel Canino: caninojm@clarkson.edu

A.2 Recruitment Letter

August 25, 2017

Dear [insert name],

Researchers at Clarkson University are conducting a research project in the development of a bionic prosthetic knee system. This research study involves the laboratory-based testing of a prototype motorized prosthetic knee system.

We are looking for adults with a transfemoral amputation (above the knee) who are/have:

- Able to ambulate with prosthesis
- Between 18 and 60 years old
- Fit with a definitive prosthesis
- Weight ≤ 200 lb

Participation would involve 6-8 sessions. The first visit should not exceed 2 hours and is for informing you of your rights if you consent to participate in the study and introducing you to the laboratory equipment with which you will interface. In subsequent sessions, you will undergo training specific to control of the prototype knee system using contractions of your hamstring and quadriceps muscles, and this training will include both nonweight-bearing and weight-bearing functions.

Once acclimated to the limb system, you will then undergo a three-day testing session where you will perform level-ground walking, slope ascent/descent, and stair ascent/descent. These functions will be performed with and without the incorporation of vibratory feedback (on your prosthetic-side forearm) to convey sensory feedback from the prosthetic limb. The objective is to evaluate the effects of such vibrational feedback on your ability to ambulate with the prototype prosthetic knee system.

We would love to hear from you. If you are interested in finding out more, please contact Kevin Fite, PhD (Principal Investigator) by phone (315-268-3809) or email (**kfite@clarkson.edu**).

We appreciate you taking the time to consider this opportunity. Your decision regarding participation will not affect you or your regular care. A consent form is enclosed so you can review it carefully prior to deciding to meet with us.

Sincerely,

Kevin Fite

Principal Investigator

A.3 Informed Consent

Clarkson University

Documentation of Informed Consent to Participate in Research

Project Title: The Use of Haptic Feedback to Enhance User Perception of an EMG-Controlled Transfemoral Prosthesis

Researcher(s): Kevin Fite, Ph.D and Joel Canino

Institutional Review Board (IRB) approval number: **Approval valid until**:

You have been asked to be a part of the research described here. Participation is voluntary.

The purpose of this study: This study will investigate the effects of sensory feedback using mechanical vibratory and pneumatic pressure stimulation on the voluntary control of a prosthetic leg.

What to expect:

Each day of training and testing for this research will last approximately two to three hours. The first few visits will focus on familiarizing you with testing procedures and control of the prosthetic limb. Please see the table provided below for an approximate time-table of the testing procedure.

After the completion of the training period, a three-day test period will begin. During the training and familiarization process, you will don the prosthetic device and be placed into a fall-prevention harness. You will then practice moving with the limb, becoming familiarized with using EMG signaling as a means of limb control. After a sufficient amount of practice time, data will be recorded for baseline gait information in level-ground walking, stair ascent, and stair descent activities. The three days of testing will involve a much shorter training period followed by the donning of the haptic feedback device on your forearm that correlates to the side of your prosthesis. You will then walk around with the haptic feedback device informing you about the prosthetic limb using one of the possible communication methods. Data will be recorded, as on the first day, for level-ground walking, stair ascent, and stair descent tasks. This process will be repeated for two more days with each day being devoted to investigating any remaining haptic communication methods.

If you have any questions about this research, you may contact the principal investigators, Kevin Fite (ph: 315-268-3809, email: kfite@clarkson.edu) or Joel Canino (ph: 315-212-8643, email: caninojm@clarkson.edu)

Day and Task	Time itment
1: Informed Consent	1 Hour
2: Prosthetic Fit and g	2 Hours
3: Training	2 Hours
4: Training	2 Hours
5: Training	2 Hours
6: Training and	3 Hours
7: Training and	3 Hours
8: Training and	3 Hours

Risks and discomforts to you if you take part in this study:

There are no invasive procedures associated with your involvement in this study.

There is a fall-risk associated with this testing, as is to be expected with the training of a new prosthetic limb. These fall risks will be greatly mitigated through the use of a fall-harness rig, which will catch you, should you lose your balance.

The benefits to you if you take part in this study:

The results of this study are not expected to be of direct benefit to you, but the knowledge gained may ultimately be of benefit to individuals with lower-limb amputations.

What will you receive for taking part in this study:

There is no compensation for taking part in this study. Participation is voluntary.

What will happen to the information collected in this study:

The information collected will be kept confidential as much as is permitted by law. Digital video will be taken of you during testing. This video will contain full-body and facial images shots from which you may be

recognizable to viewers. The video data constitutes the only personally identifiable information that will be publicly released, but public release of the video will only occur with your consent. Select **Yes** or **No** at the bottom of the page to indicate whether you permit the public release of your video data. Such public release will largely be limited to research or educational presentations associated with this study. You are not required to provide this consent in order to participate in the study. Without such consent, the investigators will not publicly release any of the video associated with your participation.

Video and de-identified experimental data collected from each session will only be released in the public domain (via publication in research journals or educational presentations to students or at conferences) after 7 days have passed. Should you choose to withdraw from this study within this 7-day window, your data will not be made public and will be deleted from the laboratory database. Should you withdraw after the 7-day window, your data will still remain unused and deleted from the database, provided that it has not already been publicly released.

What rights do you have when you take part in this study:

Participation in this research is voluntary. Deciding not to take part, or to stop being a part of this research will result in no penalty, fine or loss of benefits which you otherwise have a right to. If you have questions about your rights as a research subject or if you wish to report any harm, injury, risk or other concern, please contact Dr. Johndan Johnson-Eilola, Associate Chair of the Clarkson University Institutional Review Board (IRB) for human subjects research: (315)268-6488 or Johndan@clarkson.edu

Conflict of Interest: The Clarkson University researchers have no conflict of interest with regard to any technological developments that may result from this study.

Informed Consent: Please sign here to show you have had the purpose of this research explained and you have been informed of what to expect and your rights. You should have all your questions answered to your satisfaction. Your signature shows that you agree to take part in this research. By signing below you also attest that you are at least 18 years old. You will be given a copy of this consent form to keep for your records**.**

Yes, you can use my video:_____ No, do not reveal my video data:_____

Subject Name (Printed): _____ Subject Number: _____

Signature of volunteer: _____ Date_____

Signature of researcher

obtaining informed consent: _____ **Date:** _____

A.4 Questionnaire for Study 3

1.) How long have you been using a lower limb prosthesis?

_____

2.) What is your current model of prosthesis?

_____

3.) How long have you been using the model from question 2?

_____

4.) What do you consider to be the most limiting feature (or lack thereof) of your current prosthesis?

_____

_____

5.) Did you feel like any of the methods (Method 1 and/or Method 2) improved your perception of the prosthesis?

_____

_____

6.) Which of the haptic feedback methods (Method 1 or Method 2) did you find the most useful?

_____

_____

7.) Do you think there are any improvements that could be made to the feedback methods?

_____

_____

8.) Do you think there are any improvements that could be made to the prosthesis used during testing?

_____

_____

****

(For Investigator Use)

Investigator:

Subject ID:

Investigator Notes:

E. List of Publications and Abstracts

1. Published

Canino, J. Miles., Fite, Kevin. "Haptic feedback in lower-limb prosthesis: Combined haptic feedback and EMG control of a powered prosthesis." Proc. *2016 IEEE EMBS ICS*. IEEE, 2016.

Canino, J. Miles., Fite, Kevin. "Haptic Feedback and Rehabilitation in Powered Lower Limb Prosthetics." Proc. SB3C 2016

Canino, J. Miles., Fite, Kevin. "The Effects of Cutaneous Haptic Feedback on EMG-Based Motion Control of a Transfemoral Prosthesis." Proc. 2016 Dynamic Systems and Controls Conference, ASME, 2016

Canino, J. Miles., Fite, Kevin. "The Psychophysical Effects of Haptic Feedback in the Perceptual Awareness of a Powered Transfemoral Limb", Proc. 2017 SB3C, 2017

2. Under Review

Canino, J. Miles., Fite, Kevin., "The Experimental Evaluation of a High Resolution Haptic Feedback Array for Lower Limb Loss Rehabilitation", 2017 Wearable Robotics Conference, ASME. (In Review)

Canino, J. Miles., Fite, Kevin., "Percutaneous Haptic Feedback and its Impact on Lower Limb Loss Rehabilitation", IEEE Transactions on Haptics, IEEE (In Review)

3. Currently Writing

Canino, J. Miles., Fite, Kevin., "Percutaneous Haptic Feedback and its Impact on the Volitional Control of a Powered-Knee Transfemoral Prosthesis Control", IEEE Transactions on Neural Systems and Rehabilitation Engineering, IEEE TBD