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TITLE:
Physiologically Relevant Prosthetic Limb Movement Feedback for Upper and Lower Extremity Amputees

PRINCIPAL INVESTIGATOR:
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CONTRACTING ORGANIZATION:
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6. AUTHOR(S)

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The illusionary sensation of movement directly influences motor control through internal models. As a component of perceptual mapping of the limb muscles we are using a modified matching protocol (intentional binding) to examine how the brain responds to different visualizations of movement with respect to the vibration-induced illusionary input. This will help us to understand which muscles need to be vibrated to most effectively influence motor control. We are developing novel socket designs (EMG and Suspension Focused Design, and Vibration Tactor Focused Design) capable of integrating vibration tactors while accommodating or improving upon existing function. Gait assessment in amputees is limited because established marker sets placement is not clearly defined for prosthetics. We developed a simplified motion capture Cluster Marker Set that generates sufficiently accurate gait kinematics while allowing fast and easy marker attachment for gait assessment on the CAREN. We developed Sensory Organization Test based modules that will be stacked in an assessment package to provide outcome measures related to balance performance characteristics required to evaluate lower limb prosthesis function. Each module includes standing or walking condition sets and perturbations allowing access to different aspects of balance performance such as balance corrective response strategies and reaction times.

15. SUBJECT TERMS
Movement, Sensorimotor Control, Prosthetic, Amputee, Kinesthesia, Perceptual Illusion

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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1. INTRODUCTION:

The intrinsic feeling of limb movement (kinesthesia) is important to the use of our arms and legs yet this sense is completely absent amputees who must monitor all use of their prosthesis visually. This represents a functional departure from a biological limbs where movement and position state feedback play vital roles in the seamless execution of everyday activities. We will work to stimulate the appropriate sensory receptors in the residual muscles of the forearm (hand/wrist movement), upper arm (elbow movement), Upper leg (knee movement) and lower leg (ankle movement) to provide a physiologically relevant sense of limb movement mapped to the appropriate joints/functions of a prosthetic limb for the general amputee population. We will develop a small wearable robotic tactor interface to activate the kinesthetic receptors that remain in the residual limb. The robot will have the power to push into deeper tissue to reach and vibrate the receptors with up to 90 Hz and at least 1 mm displacement. We will use perceptual mapping to determine the functional organization of the kinesthetic receptors and establish effective modes of communication. We will use the tactor interface to project perceptions of limb movement to a prosthesis and measure function. We will do this with the following methods: 1) Joint angle matching to a physically unattached prosthesis. 2) Visual loading with eye tracking and motion capture to track visual monitoring of prosthesis use. 3) Prosthesis use with active sorting tasks analyzed in the context of optimal foraging theory. 4) Gait perturbation analysis. In order to develop devices that have clinical applicability prosthetic socket design will evolve to reflect the implementation restraints of the kinesthetic tactors.

2. KEYWORDS:

Movement, Sensorimotor Control, Prosthetic, Amputee, Kinesthesia, Perceptual Illusion.

3. ACCOMPLISHMENTS: *The PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction.*

- **What were the major goals of the project?**

Specific Aim 1: Systematically investigate the perceptions of limb movement accessible in the general amputee population.			
Major Task 1: Perceptual Mapping	**Mos.**	**% Completion**	**Date Completed**
Subtask 1: IRB	1-6	100%	31-5-16
Subtask 2: Percept Mapping	6-12	20%	
Subtask 3: Data Analysis/Manuscript Prep	13-24	N/A	
Milestone(s) Achieved: IRB Approval at all necessary sites as well as Complete Perceptual Mapping.	24	N/A	
Specific Aim 2: Tactor Integration and Testing			
Major Task 1: Tactor Device Development			
Subtask 1: Development of Experimental Tactor System	1-12	60%	

Milestone(s) Achieved: Completion of Tactor System	12	Pending	
Major Task 2: Integrate kinesthetic percepts with prosthetic limbs and perform functional testing			
Subtask 1: Tactor Integration	13-15	N/A	
Subtask 2: Matching and UE OFT and Visual Loading	16-30	N/A	
Subtask 3: Data Analysis/Manuscript Prep	25-36	N/A	
Milestone(s) Achieved: Completion Matching	36	N/A	
Specific Aim 3: Develop practical implementations of kinesthetic sensory feedback through novel socket solutions to integrate the robotic tactors in a clinically feasible manner			
Major Task 1: Novel and Clinically feasible Socket Design			
Subtask 1: Socket Design/Iteration	7-12	15%	
Subtask 2: Implementation Gait Analysis	13-30	30%	
Subtask 3: Data Analysis/Manuscript Prep	25-36	N/A	
Milestone(s) Achieved: Implementation of Socket Design	36	N/A	

- **What was accomplished under these goals?**

1) Perceptual mapping

Major activities:
IRB

Specific objectives:
Completion of required Human Subjects Research oversight requirements.

Significant results or key outcomes, including major findings, developments, or conclusions:
University of Alberta local ethics board approval was granted 24-Mar-2016. The secondary USAMRMC ORP HRPO approval was granted 16-May-2016. The Cleveland Clinic local IRB approval was granted 18-Apr-2016. The secondary USAMRMC ORP HRPO approval was granted 31-May2016. The studies at both sites are fully approved. Participant recruitment is ongoing.

Other achievements:
N/A

Stated goals not met:
None. Activity Complete

Major activities:
Percept mapping in lower limb amputee participants and able-bodied participants

Specific objectives:
Lower limb percept mapping in a trans-tibial amputee.

Significant results or key outcomes, including major findings, developments, or conclusions:
A number of sites were found where illusion-inducing vibration applied to the remaining tibialis anterior and gastrocnemius elicited percepts of movement (Figure 1). Vibration of muscles elicited a sensations of big toe movement and also a sense of the desire to move in the big toe (i.e., that the big toe was going to curl or lift but had not done so yet). These percepts were distributed at different sites below the knee. The confusion about movement percepts described above can be seen in this mapping experiment as there is both toe curling and toe lifting found at the posterior and lateral sites which are most likely associated with the remaining gastrocnemius muscle.

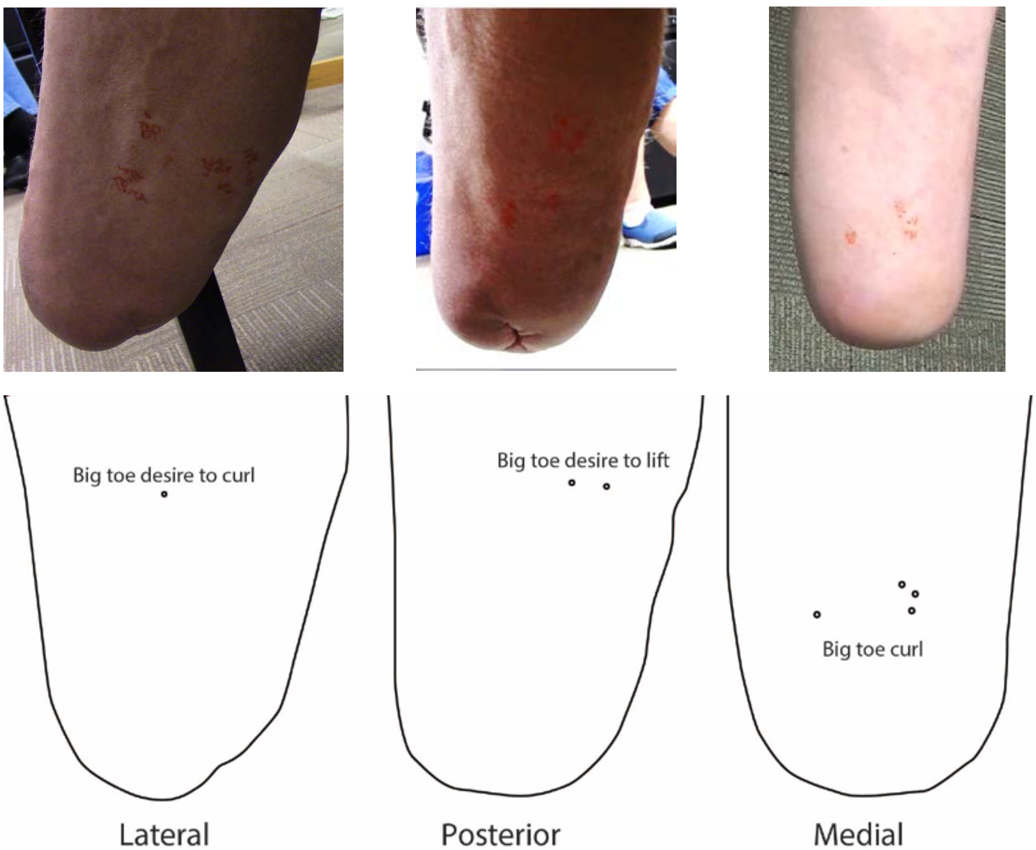


Figure 1. Lateral, posterior, and medial side of left residual limb. Locations on each of the three sides were found on different test days. Only movement and pre-movement sensations are shown.

Other achievements:

Stated goals not met:
Percept mapping is behind schedule due to staffing and training.

Major activities:
Percept mapping in lower limb amputee participants and able-bodied participants

Specific objective:
Upper Limb percept mapping in able-bodied

Significant results or key outcomes, including major findings, developments, or conclusions:

We are finding that there appears to be a confound between the vibration-induced muscle sensory receptor input and the mechanosensory input from the skin. It seems that the vibration-induced muscle sensory illusion corresponds to the contraction of the muscle (joint flexion) whereas the vibration of the skin overlying the muscle provides the sensation of skin stretching (joint extension). This causes difficulty in understanding the direction in which the limb is perceived to be moving when vibration is applied. What appears to be happening is that the vibration-induced illusionary movement input to the muscle gives the sense of movement and agency which is registered by the internal model (the brain mechanism that initiates and predicts motor actions) while the skin deflection around the joint informs conscious perception of movement direction. Our neural-machine-interface amputee population does not have this co-register of native skin and muscle and in these individuals the vibration induced perceptual illusion of movement clearly relates to the contraction movement of the muscle (joint flexion). This is important because we have found that the illusionary sensation of movement directly and instantaneously influences motor control through modulation of the internal model. As a component of perceptual mapping of the limb muscles in able bodied individuals we are using a modified matching protocol (intentional binding) to examine how their brains respond to different visualizations of movement with respect to the vibration-induced illusionary input itself (Figure 2). This will help us to understand which muscles need to be vibrated to most effectively influence motor control.

A. 

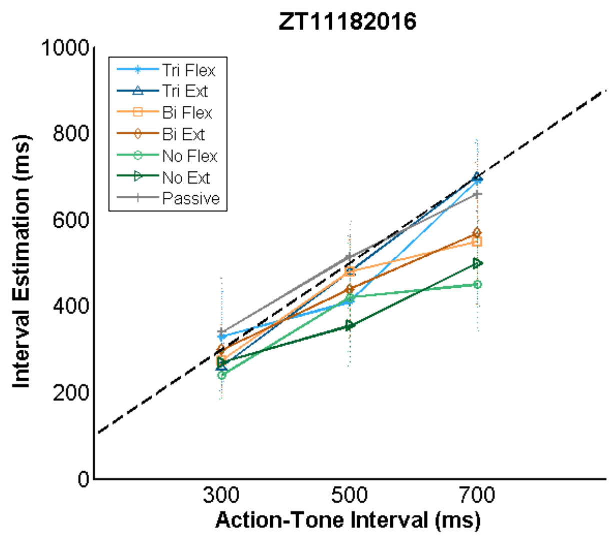
B. 

Figure 2. A) Experimental setup for evaluating match and mismatch with suspect to the vibration-induced movement illusion in able-bodied participants. The participant lays down on a table with their arm hanging in a relaxed position. When the vibration-induced movement illusion is turned on the projected visualization either flexes or extends. The participant reports their perception of the timing of the movement they see. Shorter reported latencies are tied to feeling and seeing movements that match. Longer reported latencies are tied to seeing a movement that does not match to the movement that is felt. B) Reported latencies for different actions and visualizations. There is evidence that the expected distinction between passive movement and active movement is operating (grey line vs all others); however, the relationship between the reported latencies for different induced movements and visualized movements is unclear. This is likely related to EMG control electrode placement in able-bodied so we are looking into optical tracking of movement to make the motor control signal more relevant to the physiological control of the elbow joint.

2) Novel and Clinically feasible Socket Design

Major activities:

Socket Implementation

Specific objectives:

We have had an opportunity to begin working forward in the SOW to develop novel socket designs capable of integrating vibration tactors while accommodating or improving upon the existing function. To date two designs have been produced with the intention of combing the successful attributes of each.

Significant results or key outcomes, including major findings, developments, or conclusions:
Design 1: EMG and Suspension Focused Design
This design was intended to improve suspension and EMG electrode contact, essential factors in the control and functionality of sensate prostheses. This design strategically cuts windows in the socket that are filled with a conductive plate. This plate is tied to the EMG control electronics and will contact the electrodes in the user's prosthetic liner. Therefore this plate ensures that the electrodes in the liner maintain contact with the electronics on the socket even in the event of socket slip or displacement. Additionally a BOA cable tensioning system is passed through these plates and anchored to the external surface of the socket. When tension is applied the conductive plates apply compressive forces to the residual limb, which redistributes loading and improves suspension. This design is picture in Figure 3.

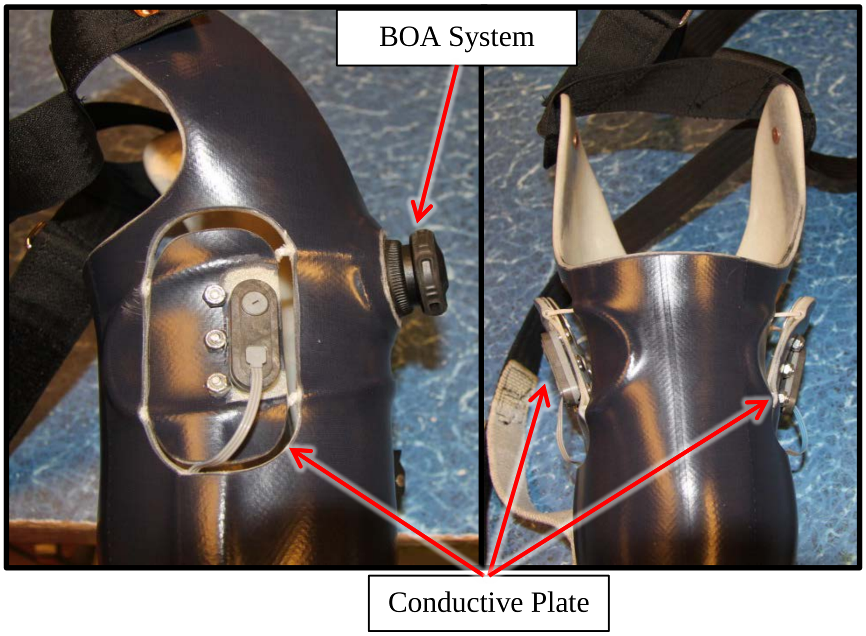


Figure 3. EMG and Suspension focused socket design

Design 2: Vibration Tactor Focused Design
The aim of this second design was to allow our vibration tactors access to the user's residual limb. Although we have performed mapping to locate appropriate anatomical locations to elicit vibration induced movement illusions, it is unclear how this soft tissue may displace once a prosthetic socket is donned. Therefore, this design allows for adjustability of the tactor location (Figure 4). The system uses a window cut in the socket and a BOA system to allow for quick re-positioning of the tactor. The BOA cable passes through a custom bases installed on the large tethered version of the kinesthetic tactor. When this cable is tensioned it applies compression to a piece Alpha liner. The high friction of the liner ensures that the tactor remains stationary on the external surface of the socket. This approach will be downscaled to integrate with the smaller non-tethered design currently in development.

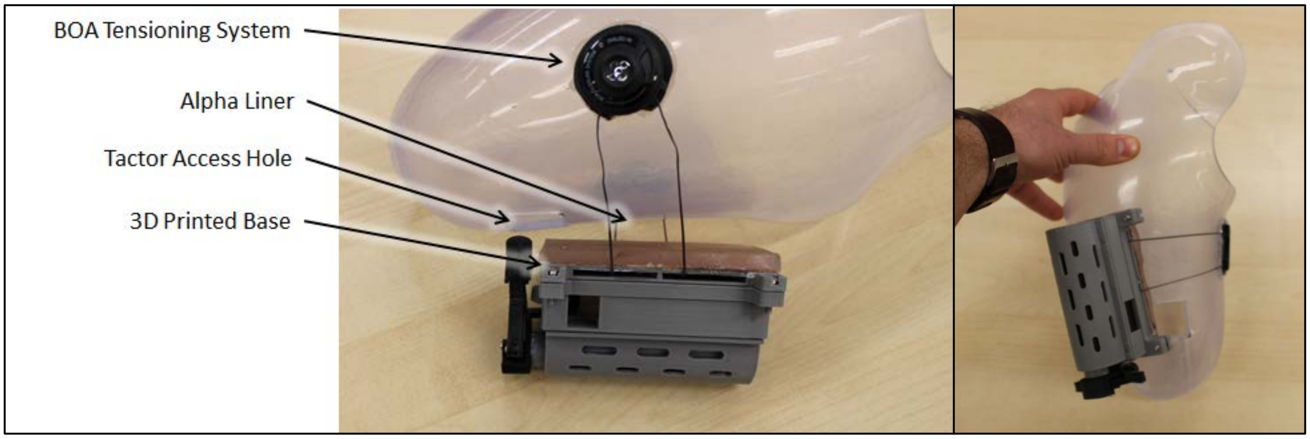


Figure 4. Kinesthetic tactor-focused design using a mock-up of our current tethered design.

Other achievements:
N/A

Stated goals not met:
N/A, we are working ahead of schedule with respect to the SOW.

Major activities:
Lower Limb Implementation

Specific objectives:
Measures of motion and balance

Significant results or key outcomes, including major findings, developments, or conclusions:
Traditionally, gait assessment relies on motion capture via body-affixed markers, requiring a trained clinician to appropriately attach the markers to anatomic landmarks on the subject. Gait assessment in individuals with amputation, using any of the well-established marker placement sets (e.g., Helen-Hayes Marker Set - HMS), is limited because marker placement on the prosthesis is not clearly defined. We developed a simplified motion capture Cluster Marker Set (CMS) that generates sufficiently accurate gait kinematics while allowing fast and easy marker attachment for gait assessment on the CAREN. The CMS consists of a set of seven plates, each holding four reflective markers, to be attached on each of the segments defining the lower limb (i.e., pelvis, 1; thighs, 2; shanks, 2; feet, 2). The plates have been designed to be easily and rapidly attached to each segment by use of elastic Velcro straps. Traditionally, clustered markers sets need either to be carefully aligned to the corresponding segment main axis, or to be calibrated using additional body landmarks. As part of the CMS, we designed a functional calibration protocol that does not require plates to be placed in a particular orientation nor require specific landmarks for calibration. Calibration for the CMS is performed by running a calibration algorithm with motion data captured from a sequence of pre-set calibration movements (sit-to-stand routines) to be performed once the plates are in place. We have collected pilot data that has shown the use of the CMS is appropriate for the kinematic measurements necessary to assess gait. We plan to collect additional data to formally validate the CMS for reliability and repeatability.

Specific objectives:
Balance performance assessment

Significant results or key outcomes, including major findings, developments, or conclusions:
Different tests already exist to measure the effect of sensory feedback in balance control during standing. The most commonly used tests are different variations of the sensory organization test (SOT). The SOT allows testing of balance

control during standing for different conditions aimed at testing the effect of the visual, vestibular and proprioceptive systems during balance. Balance after lower limb amputation is challenged during standing but the challenge becomes more relevant during walking. We have already integrated the SOT into the CAREN and are now finalizing developing a set of SOT-based tests to expand the test to measure balance performance during standing and walking.
The lack of sensory feedback from the amputated limb results in a challenge to the nervous system to regulate balance. This challenge is further increased when balance is challenged by perturbations such as those resulting from tripping or slipping. In particular, responses to perturbations are difficult for lower limb users to modulate because of the lack of information about the onset of the perturbation as well as the perturbation characteristics such as type (e.g., trip vs slip) and magnitude. We have defined a set of reactive tests to be performed to the CAREN that will challenge balance by delivering perturbations of different types and magnitudes to measure balance reactive performance.
The aforementioned balance performance tests will be ran on the CAREN as a set of modules. We have developed different modules that will be stacked together as an assessment package that will provide outcome measures related to the different balance performance characteristics that need to be tested to evaluate lower limb prosthesis function. Each module consists of a set of standing or walking conditions and perturbations that will allow us to tease out different aspects of balance performance such as balance corrective response strategies and reaction times to balance perturbations.

Specific objectives:
Assessment modules pilot testing

Significant results or key outcomes, including major findings, developments, or conclusions:
We are currently developing the programs necessary to run the test modules on the CAREN. Once the programs have been installed and ready to run, we will be collecting data on healthy participants to evaluate the assessment tool (i.e., modules of performance). This will lead to refinements of the protocol in preparation for validation testing on lower limb prosthetic users.

Other achievements:
N/A

Stated goals not met:
N/A, we are working ahead of schedule with respect to the SOW.

3) Tactor Device Development

Major activities:
Wearable Untethered Tactor Development

Specific objectives:
Design Iteration

Significant results or key outcomes, including major findings, developments, or conclusions:
The new proprioception tactor concept is based on a fixed displacement cam which is used to convert the rotational motion of the motor into the reciprocating motion of the tactor head (Figure 5). In this architecture the motor runs at constant speed rather than following a sinusoidal profile as in our previous approach dramatically reducing the necessary acceleration and torque requirements. This approach trades off the variable displacement capability (recent studies have confirmed that a fixed 1 mm displacement is sufficient for eliciting the proprioception illusion) for a substantially smaller tactor package. The frequency of vibration is still adjustable by controlling the motor speed.

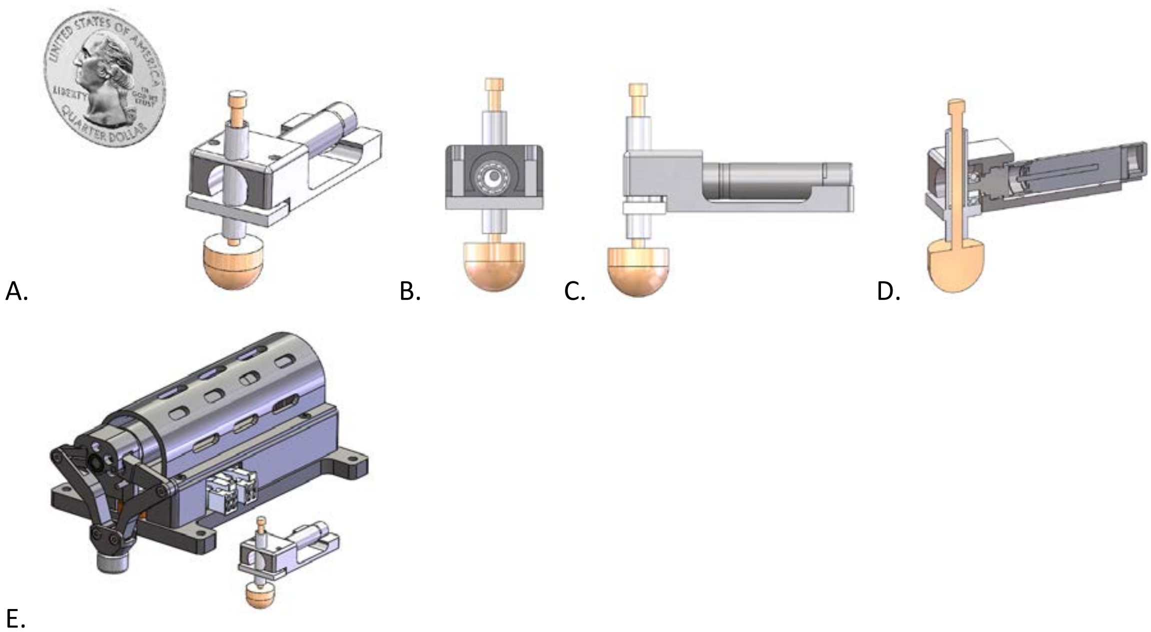


Figure 5. Lightweight, wearable, battery-powered kinesthetic tactor design. A, B, C) Scale, front and side views of the wearable kinesthetic tactor. D) Cutaway showing motor and fixed displacement cam configuration. E) A size comparison between the current tethered kinesthetic tactor and the new design for the wearable kinesthetic tactor (see figure 1A). The design for this project will still reach the same frequency and displacement as the tethered device but will draw far much less power.

Other achievements:
N/A

Stated goals not met:
This goal is behind schedule due to administrative subcontract obligation delays and staffing. While design iteration is underway we have utilized our larger tethered kinesthetic tactors for socket design and testing as needed.

- **What opportunities for training and professional development has the project provided?**

Nothing to report (project not intended to provide training or professional development opportunities)

- **How were the results disseminated to communities of interest?**

Nothing to report

- **What do you plan to do during the next reporting period to accomplish the goals?**

Tactor development will progress to physical prototype devices. Mapping and testing studies will utilize our current tethered kinesthetic tactor until the new version is available for implementation. Study participant recruitment will continue. We currently have a new trans-femoral amputee scheduled for percept mapping experiments in the 2nd week of December. Able-bodied participants will be scheduled to continue matching and percept mapping experiments. We are accessing two new clinical sites for potential upper limb amputee recruitment.

4. **IMPACT:** *Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project relative to:*

- **What was the impact on the development of the principal discipline(s) of the project?**

As described above, there is debate in the movement perception field about the roles of muscle movement sensation and skin sensation at the joints for determining how a limb is felt to be moving. We have evidence from our current work in neural-machine-interface amputees to suggest that the vibration-induced movement illusion interacts directly with the brain mechanism that initiates and controls intended movements. We are working on using the work we are conducting in this project to help inform the science of sensory feedback for motor control.

- **What was the impact on other disciplines?**

Nothing to Report

- **What was the impact on technology transfer?**

Nothing to Report

- **What was the impact on society beyond science and technology?**

Nothing to Report

5. **CHANGES / PROBLEMS:**

- **Changes in approach and reasons for change**

We have instituted a more sophisticated matching paradigm to our perceptual mapping approach to provide insight into how the brain integrates movement visualizations to help us more effectively target the appropriate muscle groups for vibration-induced illusionary movement perception.

- **Actual or anticipated problems or delays and actions or plans to resolve them**

Administrative subcontract and staffing slowed device development and percept mapping. All project sites are fully staffed and work is now proceeding on pace. In an effort to balance delays we worked forward in the SOW on lower limb implementation and socket design. Overall the project is on track.

- **Changes that had a significant impact on expenditures**

At Cleveland Clinic bringing in the correct post-doctoral fellow with the necessary skills to take a leadership role in conducting experiments took longer than anticipated. We were set back 5-6 months, however all staff are on-site, trained and producing data. HDT is a commercial company. They were involved with previously scheduled projects at the time that this effort was obligated. As soon as staffing was available to begin this project they started. Although the start date was delayed HDT is currently on pace with device development. At University of Alberta their account for year 1 just opened in June 2016 (which officially was supposed to start Sept 1, 2015). University of Alberta could not start work until after the grant opened. They now have an extension to year end Dec 2016 and are on pace but will need to carry over most funds to year 2.

- **Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents**

None

- **Significant changes in use or care of human subjects**

None

- **Significant changes in use or care of vertebrate animals.**

N/A

- **Significant changes in use of biohazards and/or select agents**

N/A

6. **PRODUCTS:**

- **Publications, conference papers, and presentations**

Nothing to Report

7. **PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS**

- **What individuals have worked on the project?**

Name:	*Paul Marasco*
Project Role:	*PI*
Researcher Identifier (e.g. ORCID ID):	*N/A*
Nearest person month worked:	*3.6*
Contribution to Project:	*Project oversight. Study Design. Data interpretation.*
Funding Support:	*N/A*
Name:	*Courtney Shell*
Project Role:	*Post-Doctoral Fellow*
Researcher Identifier (e.g. ORCID ID):	*N/A*
Nearest person month worked:	*6*

Contribution to Project:	*Study Design. Data Collection*
Funding Support:	*N/A*
Name:	Jacqueline Hebert
Project Role:	Subcontract PI University of Alberta
Researcher Identifier (e.g. ORCID ID):	N/A
Nearest person month worked:	1.2
Contribution to Project:	Lead of research design, implementation and conduct of research at site
Funding Support:	University salary supported
Name:	Juan Forero
Project Role:	Post doctoral associate
Researcher Identifier (e.g. ORCID ID):	N/A
Nearest person month worked:	4
Contribution to Project:	Development of lower limb outcome metric to be used for investigating the impact of lower limb proprioceptive feedback.
Funding Support:	N/A

- **Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?**

No

What other organizations were involved as partners?

- **Organization Name:** University of Alberta
- **Location of Organization:** Canada
- **Partner's contribution to the project:** Subcontract, Kinesthetic Experiments
- **Collaboration:** Both laboratories work on project goals and share results
- **Organization Name:** HDT Robotics
- **Location of Organization:** USA
- **Partner's contribution to the project**: Subcontract, Device Development

- **Collaboration:** Wearable Kinesthetic Tactor Development
- **Organization Name:** Cleveland VA
- **Location of Organization:** USA
- **Partner's contribution to the projec**t: Subcontract, Access to VA amputee population, project staff.
- **Collaboration:** Prosthetics/engineering support

8. **SPECIAL REPORTING REQUIREMENTS**

N/A