LONG-TERM FUNCTIONAL IMPROVEMENT WITH DEXTEROUS PROSTHETIC LIMB

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ABSTRACT

Advanced myoelectric prosthetic devices aim to restore functional capability after upper limb loss. However, studies of their functional impact have been mostly limited to short-term clinical studies which rely on assessments of simple manual tasks. Here we show that a longer term study can elucidate functional improvement and quantify how and when a prosthesis is used. A participant with transhumeral amputation and an osseo-integrated interface participated first in a ten-day study of functional capability with a highly prosthesis, the Modular Prosthetic Limb (MPL). A few months later, he took the MPL home and used it daily for 12 months. He returned to the laboratory for functional assessments every two months. We measured improved scores in Assessment of Capability with Myoelectric Control, Box and Blocks Test, and NASA Task Load Index over the course of the long-term phase. Only slight improvement was documented over the short-term clinic-based phase, which suggests that longer studies may be required to assess capability with highly dexterous prosthetic limbs. Additionally, the loads experienced by the limb in the home environment were much greater than during the laboratory visits, which suggests that the functional assessments do not capture the full spectrum of loads placed on a prosthesis during activities of daily living. Through the combination of functional outcome measures, on-board data logging, and long-term studies in the home environment, we are developing the capability to assess upper limb rehabilitation progress and device appropriateness.

INTRODUCTION

For people with upper limb loss, use of a prosthesis has been correlated with higher quality of life and rates of employment, but prosthesis abandonment persists. In recent studies, rejection rates range from 18% in the general US population [1] to 40% in the Veteran population [2]. Lack of function is the most widely reported cause of abandonment [1]–[3].

Myoelectric prostheses aim to restore functional capability, and commercially available terminal devices range from a powered hook to a multi-finger multi-grip prosthetic hand like the bebionic (Otto Bock, Berlin), capable of 14 selectable grips. The Modular Prosthetic Limb (MPL) is a research prototype with 17 independent actuators and infinitely configurable grips [4], [5]. Advanced devices like the MPL further extend the dexterous capability of upper limb prostheses. To match a given user's needs to a prosthesis in terms of dexterity, robustness, and usability, clinicians rely on functional outcome measures. However, these outcome measures have documented limitations [6], and even high quality measures neglect performance of domestic, everyday tasks. In contrast, long-term studies of prosthesis use in the home could elucidate how and when a prosthesis is used in activities of daily living and show functional progress. To date, this kind of study is rare and generally limited in duration to a few weeks or months [7]–[9]. Additionally, the time to train and master control of high degree of freedom prosthetic limbs is unknown.

We aimed to evaluate the functional capability of the MPL through a 12-month study. We collected continuous sensor data from over 100 sensors within the MPL including torque data from the device attachment site during daily use, and we intermittently assessed the user's functional progress with in-clinic outcome measures. Our results provide insight into the value of long-term evaluation of advanced upper limb prosthetic limbs.

METHODS

Our participant was a 63-year old male who underwent transhumeral amputation in 2007 secondary to cancer. The participant received targeted muscle reinnervation in 2012 and an osseo-integrated (OI) implant in 2015. Prior to starting the study, the participant had approximately 80 hours of experience with the MPL in a user-feedback and demonstration capacity. He provided informed consent, and all research activities were approved by the Institutional Review Board at Walter Reed National Military Medical Center.

We analysed the participant's data from two research efforts. First, he completed a ten day clinic-based study of the MPL with 11 other prosthesis users in May 2017. The study consisted of 12 laboratory training sessions of one to two hours each. Assessments of the MPL against his conventional prosthesis were conducted at the study's initiation, midpoint, and exit. The assessments were the Assessment of Capability with Myoelectric Control (ACMC) [10] and the Box and Blocks Test (BBT) [11]. The NASA Task Load Index (NASA-TLX) [12], a survey measure of mental load during a task, was performed after the ACMC and BBT. The second effort was the 12-month home study. During this phase, the participant was encouraged to wear the MPL for at least three hours a day during his activities of daily living. We evaluated his functional progress in clinical sessions every two months, and the same outcomes measures (ACMC, BBT, and NASA-TLX) were scored.

We also continuously monitored the loads on the OI interface throughout the home use phase of the study. Sensors mounted on the MPL measured the rotational torque (torsion) along the long axis of the humerus. Additional sensors measured the bending torque on the elbow joint about the elbow flexion/extension axis. We compared the loads on the arm in the clinical and home environments.

RESULTS

In the last session of the short-term, clinical phase of the study, the participant expressed that he had greater control of the MPL than at the start of the study, but that knew he could get better with more practice. This sentiment is reflected in the ACMC and BBT scores, which showed only slight improvement over the short term (Figure 1). The participant's prediction of his long-term improvement was correct. After approximately 100 days of home use, both the ACMC and BBT scores improved. Furthermore, the NASA-TLX results indicated that the mental load experienced by participant during the ACMC and BBT measures decreased over time.

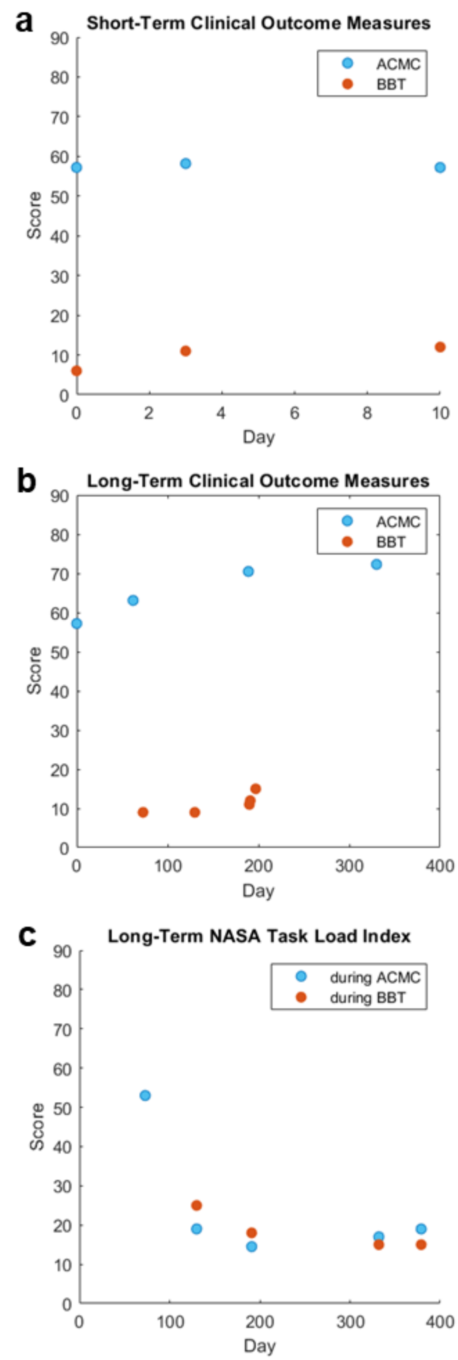

Figure 1. Clinical outcome measure scores. a) ACMC and BBT with the MPL during the short-term clinical study were relatively static. **b)** ACMC and BBT scores increased over the long-term, with the best scores recorded at the exit assessment. **c)** The NASA-TLX survey was administered after the ACMC and BBT. Lower scores on this measure indicate that lower mental load is required to complete a task.

Next, we compared the loads experienced during the clinical sessions of the 12-month home use study with the data recorded while the participant used the prosthesis at home. We recorded approximately 4.4 hours of wear a day during the take-home phase of the study and a total of 850 hours of data. We compared the elbow torque and OI torsion experienced by the limb during home use and during the six clinical sessions. Both elbow torque and OI torsion were much higher in the home environment than the clinical environment (Figure 2), which indicates that higher loads were placed on the MPL during the unstructured tasks of daily living than during the clinical functional assessments.

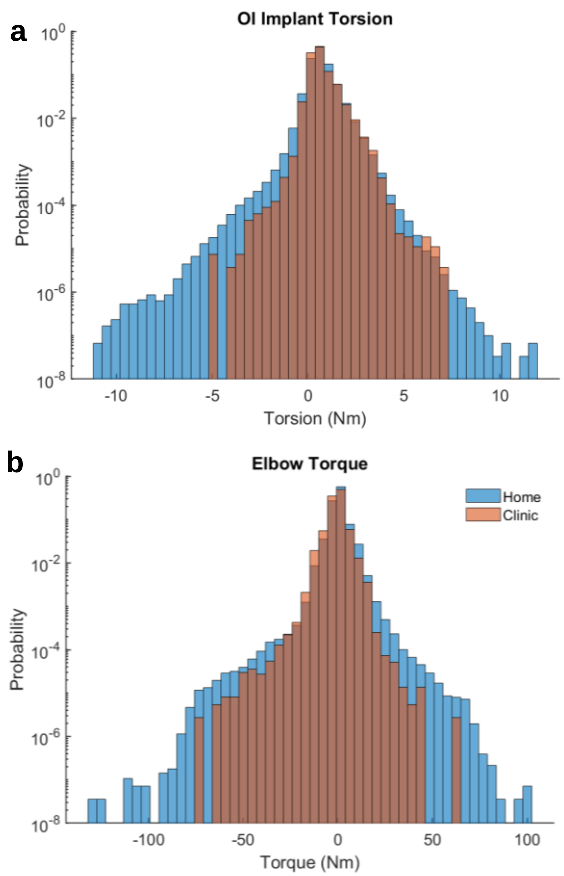

Figure 2. Histograms comparing loads on the MPL. For both graphs, the y-axis units are is the probability that a given data capture would be at a given torque. That is, higher probabilities correspond to more commonly measured torques. **a)** The torsion experienced at the OI interface was higher in the home environment (blue) than the clinical environment (orange). **b)** The elbow torque during all clinical sessions varied greatly from the torque recorded during home use of the MPL. The maximum torque magnitude in the clinical setting was 65 N-m compared to 135 N-m at home.

DISCUSSION

Our results suggest that a long-term study can capture functional progression with an advanced prosthesis even when progression is not evident over the short term. In the earlier study of 11 participants that compared the MPL with the participants' conventional prostheses, the MPL was found to out-perform the conventional prostheses, but gains in functional improvement over the two- to four-week study were unexpectedly low for some users. After that study, we expected that with increased wear time, a user's functional performance with the MPL would improve, and the longer term progress documented here supports this hypothesis. Additionally, the varied tasks demanded by the home environment could have contributed to increased capability over time. The participant reported frequent travel, daily meal preparation, and highly dexterous tasks like playing the piano. These tasks were demanding from a control perspective and likely contributed to the improvement in functional outcome scores. Furthermore, the increased functionality might have been a motivating factor to the participant's acceptance of the MPL, since his hours of continuous usage, the times he used the MPL without doffing, increased throughout the study.

The loads experienced by the limb during activities of daily living were much greater than during clinical assessments. This result has implications for the design requirements of new prostheses. Although we did not temporally map the higher torque loads to specific activities, the participant reported stressing activities like clearing his garden with power tools which could account for the higher torque. The high torsional values we recorded are consistent with data from intact limbs during advanced activities of daily living [13]. The frequent loads (50 N-m and 5 N-m for bending torque and torsion, respectively) are similar to loads previously reported from single session studies of OI transhumeral amputees [14]. Prosthesis users with OI implants have expressed concern about overloading the OI implant [14], and more data from active users like our participant could ease those concerns. Further studies could help shape the requirements for the safe use of an OI implant.

Through the combination of functional outcome measures, on-board data logging, and long-term studies in the home environment, we are developing the capability to assess upper limb rehabilitation progress and device appropriateness. In particular, our on-going work includes passive data collection methods such as wrist accelerometers and joint sensor data to monitor user performance.

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