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Portable System for Home Use Enables Closed-Loop, Continuous Control of Multi-Degree-of-Freedom Bionic Arm

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***Abstract*—Commercial prosthetic hands are frequently abandoned due to unintuitive control methods and a lack of sensory feedback from the prosthesis. Advanced neuromyoelectric prostheses can restore intuitive control and sensory feedback to prosthesis users and potentially reduce abandonment. However, not all advanced prosthetic systems are deployable for home use on portable systems with limited computational power. In this work, we use a commercially available portable neural interface processor (the Ripple Neuro Nomad), and a multi-degree-of-freedom bionic arm (the DEKA LUKE Arm) to create a closed-loop neuromyoelectric prosthesis. The system restores intuitive, independent, continuous control over the arm's six-degrees-of-freedom and provides sensory feedback for up to 288 neural and six vibrotactile channels. Additionally, the large storage capacity of the system enables high-resolution logging of EMG, hand positions, prosthesis sensors, and stimulation parameters. We developed two GUIs enabling wireless, real-time adjustments to motor control and feedback parameters: one with nearly full control over motor control and feedback parameters for investigators, and one with restricted capabilities enabling end-user safety. We verified the system's closed-loop function through a fragile egg task with vibrotactile sensory feedback. We tested the neural stimulation with an amplifier capable of eliciting transcutaneous percepts. This neuromyoelectric prosthetic system will be used for an extended take-home trial that could provide strong clinical justification for advanced, closed-loop prostheses.**

***Clinical Relevance*— This work establishes an advanced, intuitive, sensorized prosthesis that can be used in home and clinical settings.**

I. INTRODUCTION

Upper-limb prosthesis users abandon commercially available prostheses at rates up to 50% [1]. Restoring sensory feedback and intuitive control over bionic arms could reproduce sensorimotor function similar to that of the endogenous hand and thereby reduce abandonment.

Sensory feedback is an integral component missing in most commercially available prostheses, which is a major factor in prosthesis abandonment [2]. Sensorized prostheses help users to experience their prosthesis as their own hand [3], [4], not just a tool, and improve a wide range of psychosocial factors [5].

Deploying sensory-enabled prosthetic systems with advanced control algorithms for home use is not necessarily feasible on portable systems with limited computation. In this work, we report on our use of commercially available hardware to create a closed-loop, portable system capable of providing intuitive, continuous prosthesis control and sensory feedback through vibrotactile and electrical stimulation. We demonstrate closed-loop continuous control with vibrotactile feedback. In the near future, this system will be used for closed-loop, neuromyoelectric control of the LUKE Arm in a long-term take-home trial.

II. METHODS

A. Portable Neural Interface Processor

We used a Nomad neural interface processor (Ripple Neuro, Salt Lake City, UT, USA) for this study. The Nomad runs on Linux 8 (jessie) with an Intel Celeron processor (N2930) at 1.83 GHz with 2 GB RAM and 500 GB storage. The system described herein (Fig. 1a) builds upon the system described in [6]. In short, the original system provides continuous control for up to six independent degrees of freedom, the number of degrees-of-freedom of the LUKE Arm, using a modified Kalman filter. The original system acquires 32 channels of electromyographic inputs for prosthesis control, calculates the 496 differential pairs of the 32 channels, performs channel selection to choose 48 channels for decoding, then trains a modified Kalman filter. Because of the large storage capacity of the Nomad, the system can record an extensive dataset including electromyography, hand positions, and force sensor information from the prosthesis.

Notable new features to the system include: (1) electrical and vibrotactile sensory feedback enabling closed-loop control; (2) two GUIs for real-time adjustments to movement and sensory feedback parameters; and (3) additional motor control adjustments. Also, due to discontinued support of the original C API for accessing data streams on the Nomad, the new system was rebuilt using Python 3.4 and a Python API for accessing data streams on the Nomad.

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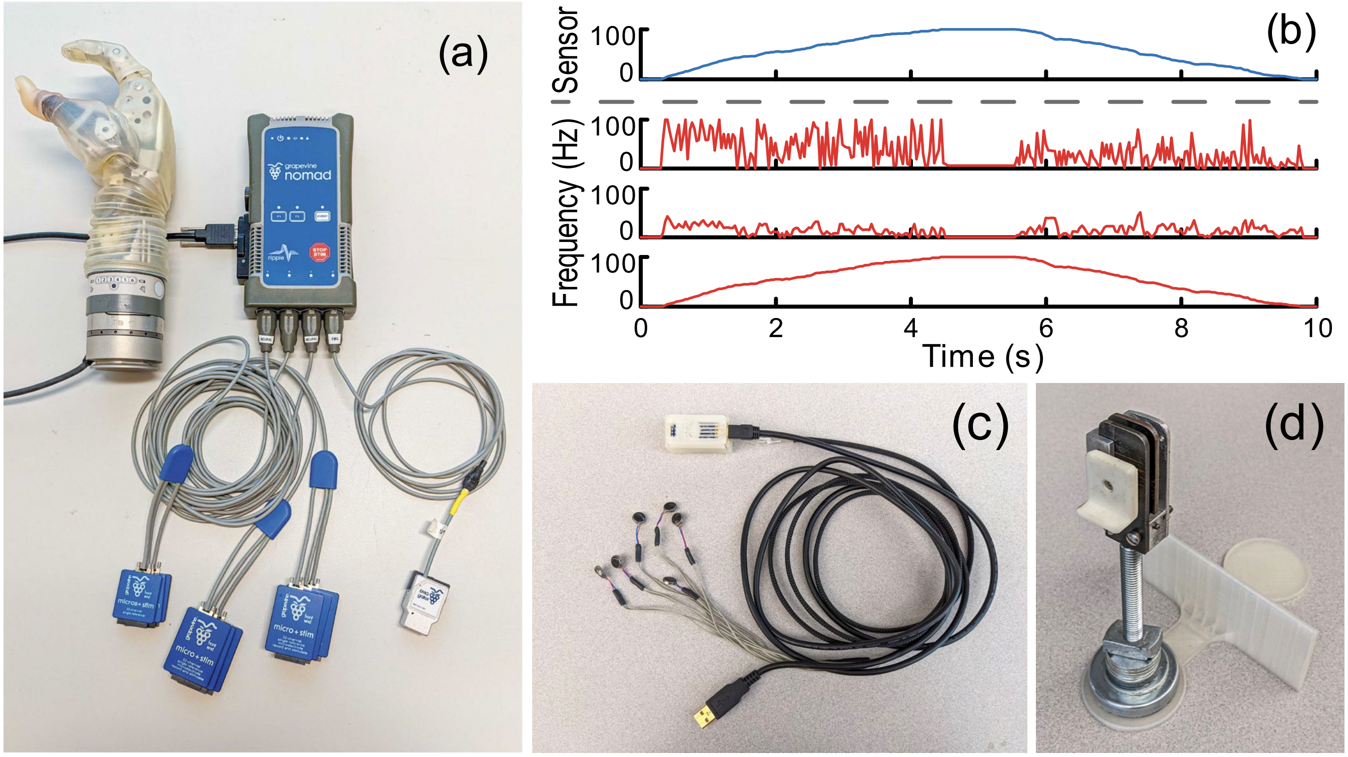

Fig. 1 Portable system enables closed-loop prosthesis for take-home use. **(a)** The Ripple Nomad neural interface processor can provide stimulation for up to three 100-channel Utah Slanted Electrode Arrays and record 32-channel EMG to control a prosthesis (DEKA LUKE Arm). **(b)** Activating sensors (top trace; blue) on the prosthesis modulates the frequency of electrical stimulation for a biomimetic primate model (second from top; red), biomimetic rapidly adapting model (third from top; red), and linear activation (bottom; red). **(c)** A vibrotactile stimulator enables simple closed-loop control verification. **(d)** The fragile egg test was used to verify closed-loop function.

1) Electrical and Vibrotactile Sensory Feedback

Our addition of sensory feedback enables closed-loop prosthesis use, a major thrust in advanced prosthesis research. The system can provide electrical stimulation for up to three 100-electrode Utah Slanted Electrode Arrays based on sensor readings from the LUKE Arm. The system has three stimulation algorithms implemented: a biomimetic model developed from recordings of nonhuman primate cutaneous afferents in response to physical contact with the fingertip [7], a biomimetic model based on rapidly adapting mechanoreceptors [8], and a traditional linear model. We have also developed an amplifier (±150V), based on [9], to provide transcutaneous stimulation, which aided in verifying and debugging electrical stimulation.

We also developed an Arduino-based, six-channel vibrotactile stimulator (Fig. 1c) that uses 10 mm x 3 mm vibration motors. Stimulus intensity for the vibrotactile stimulation increases linearly with sensor values from the prosthesis.

2) GUIs for Real-Time Adjustments

We developed two GUIs that enable real-time changes to motor and sensory functions, one for investigators, and one for end-users. Both GUIs communicate with the Nomad over Wi-Fi and can be controlled remotely, enabling investigators to update the system and assist the end-user during a take-home trial.

The investigator GUI (Fig. 2c) displays EMG features, kinematic values, sensor data from the prosthesis, and computational load on the system. Investigators can start and stop stimulation and change all sensory feedback parameters (within previously determined safety limits), including: the prosthesis sensors driving stimulation, the algorithm used to provide stimulation, and the channel to stimulate. The minimum and maximum stimulation amplitude and frequency can be adjusted per channel. Investigators can adjust motor control parameters, including: locking a degree-of-freedom in a specific position or setting it to mimic another degree-of-freedom, starting a decoder training, and disabling broken electrodes.

The end-user GUI (Fig. 2a-b) provides similar functionality to the investigator GUI with respect to motor control but limits the user's control over sensory feedback. End-users can change minimum stimulation amplitude and turn pre-set channels on and off, but the stimulation channel, maximum stimulation amplitude, and stimulation frequencies cannot be modified. These limits ensure that stimulation parameters stay within safe limits.

3) Motor Control Adjustments

Degrees-of-freedom can be programmatically locked in a specific position or set to mimic another degree-of-freedom, which may be beneficial when control for a particular degree-of-freedom is unreliable. Electrodes can also be specified such that they will not be used for prosthesis control, which could be preferable in the case of broken electrodes. Channel selection, which is the most time-intensive portion of training the system, runs as a background process, enabling the user to continue interacting with the system (e.g., to test stimulation settings) without interruption. Lastly, the system automatically

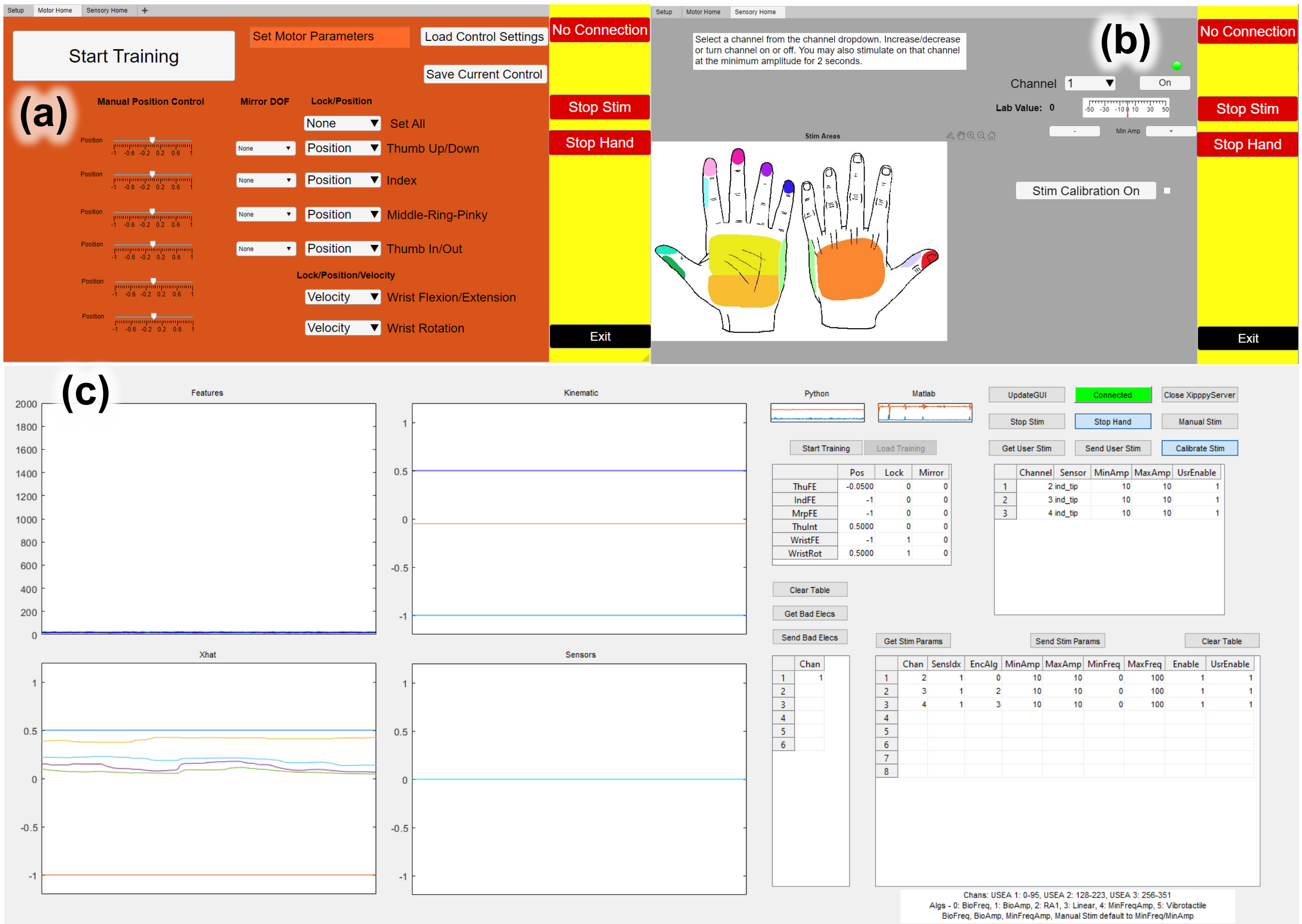

Fig. 2 End-user and investigator GUIs enable real-time adjustments to motor and sensory functions. **(a)** End-user GUI enables user to start decoder training and fine-tune motor control parameters. **(b)** End-user GUI enables user to adjust some feedback parameters and turn feedback on/off. **(c)** Investigator GUI visualizes EMG, kinematics, decoder predictions, and prosthesis sensor values, and allows investigators to fine-tune a variety of motor control and sensory feedback parameters.

saves decode parameters so that motor control can be resumed without retraining or transferring the parameters through a tablet.

B. Closed-Loop Fragile Egg Task

1) Human Subjects

One male participant, 44, having a bilateral transradial amputation, completed this study. The participant's amputations were 11 years prior to this study. Informed consent and experimental protocols were completed in accordance with the University of Utah Institutional Review Board.

2) Prosthesis Setup

We evenly spaced 34 Covidien Kendall™ disposable surface electrodes below the right elbow of the participant, with the reference and ground electrodes over the elbow. Two vibrotactile motors were placed at the distal end of the limb, close to the location where the participant felt their phantom thumb and index finger. The electrodes and stimulator were covered in Coban™ self-adhering wrap. We then placed a custom, 3D-printed, universal socket over the electrodes, and attached the LUKE Arm to the socket.

The vibrotactile motors were tied to the sensors in the thumb and index fingers of the LUKE Arm, and increased linearly with increasing force. We set the baseline vibration such that the participant could feel small sensor activations and set the maximum vibration to the maximum of the sensors.

To train the system, the participant mimicked pre-programmed hand opening/closing movements and wrist flexion/extension of the LUKE Arm. A single trial consisted of a 0.7 s transition to the intended motion, a 4-s hold, and a 0.7 s transition back to resting position. The participant completed four trials of each movement.

After the mimicked training, the Nomad proceeded with a Gram-Schmidt channel selection algorithm to choose 48 optimal features and then use those features to compute the Kalman filter matrices for a steady-state Kalman filter [6]. After the feature selection and Kalman filter matrices

Table 1. Times for Training Portable System for Fragile Egg Test with Vibrotactile Sensory feedback

Training	
Mimicking Prosthesis	110 s
Channel Selection	87 s
Steady-State Kalman Training	2.3 s
Testing	
Runtime loop (including data acquisition, decoding, stimulation, and file saving)	6.7 ms

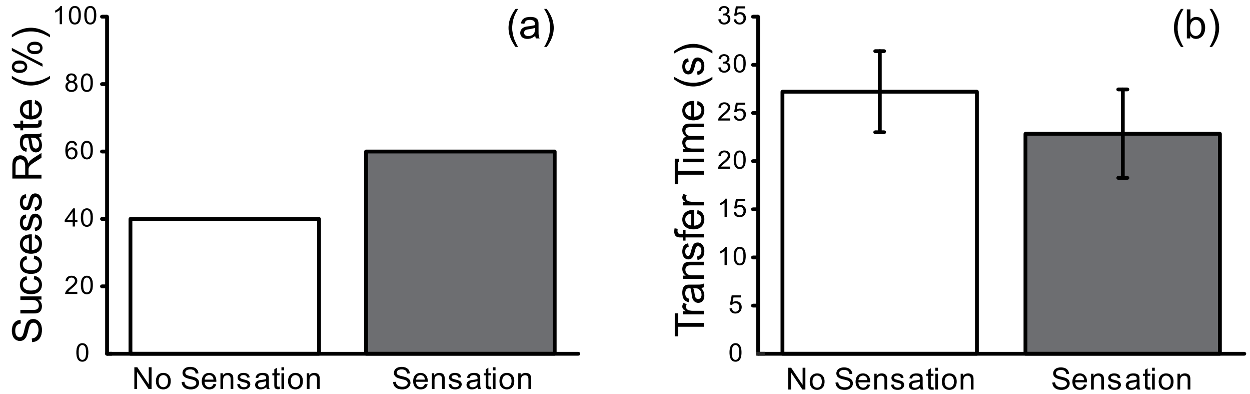

Fig. 3 Fragile egg test with vibrotactile feedback verifies functionality of closed-loop system. **(a)** The participant successfully transferred the fragile egg 60% of the time with sensation, versus 40% without sensation (n = 15 trials; p = 0.12, binomial test). **(b)** The participant transferred the fragile egg in 22.8 ± 4.6 s (mean ± SEM) with sensation (n = 9 successful trials), versus 27.2 ± 4.2 s (mean ± SEM) without sensation (n = 6 successful trials; p = 0.52, two-sample t-test).

calculations were completed, control of the prosthesis was automatically transferred to the user.

3) Fragile Egg Task

The fragile egg task (Fig. 1d) was developed to show the benefits of sensorized prostheses [10]. The objective of the task is to move the egg horizontally 15 cm from one side of a 6.25 cm vertical barrier to the other without "breaking" the egg. If the grip force on the fragile egg exceeds the break force, an audible click is emitted, representing a "break."

The participant completed 15 trials of the fragile egg task with and without vibrotactile feedback. For each trial, the participant started a timer, transferred the egg, then stopped the timer. Prior to recorded trials, the participant practiced the task with and without sensory feedback for approximately five minutes. We measured both the success rate (transfers without breaking the egg) and the time for each egg transfer. We used a mechanical fragile egg weighing 496 g with a break force of approximately 17 N.

III. Results

A. Portable System Enables Closed-Loop Prosthesis Control

We verified that the Nomad system (Fig. 1a), rebuilt in Python, successfully acquired 32-channels of surface EMG and used a modified Kalman filter for continuous control of the LUKE Arm. Through the GUI, individual degrees-of-freedom could be locked or set to mimic other degrees-of-freedom in real-time.

We tested electrical stimulation with a 150V amplifier capable of providing transcutaneous stimulation [9]. The system successfully produced transcutaneous percepts with both biomimetic stimulation algorithms and the linear stimulation algorithm when sensors on the prosthesis were depressed. Fig. 1b shows an example of sensor activation (top blue trace) and resultant stimulation frequencies (bottom three red traces). The lower three red traces in Fig. 1b show the stimulation frequency driven by the sensor activation using the biomimetic primate model (top) [7], biomimetic rapidly adapting model (middle) [8], and linear activation (bottom). We also verified the Arduino-based vibrotactile stimulation (Fig. 1c), which uses a linear activation model.

B. Closed-Loop Fragile Egg Test

The participant successfully transferred the fragile egg 9/15 times with vibrotactile sensory feedback, versus 6/15 times without (Fig. 3a; p = 0.12, binomial test). With sensory feedback, the participant took 22.8 ± 4.6 s (mean ± SEM) to complete the task, versus 27.2 ± 4.2 s (mean ± SEM) without sensory feedback (Fig. 3b; p = 0.52, two-sample t-test). Computational training and testing times for the fragile egg task are shown in Table 1.

IV. Discussion

Using commercially available technologies, we have developed a portable prosthesis system capable of closed-loop, continuous control of a six-degree-of-freedom bionic arm. We demonstrated the system's ability for closed-loop control through a fragile egg task using vibrotactile sensory feedback, which improved the users control of the prosthesis. We also verified electrical stimulation through a transcutaneous stimulator. This system will be used in the future for a take-home trial with an advanced neuromyoelectric prosthesis.

The ability to stimulate up to 3 intraneural Utah Slanted Electrode Arrays (with nearly 100 channels each) and to provide independent, continuous control over the six-degree-of-freedom LUKE Arm in a portable system provides a strong opportunity to showcase the benefits of closed-loop prostheses with high-fidelity tactile feedback and intuitive motor control. The in-laboratory and short-term, at-home benefits of similar closed-loop systems have been promising [3], [8]. We anticipate further benefits with extended at-home use, ultimately providing strong justification for more advanced prostheses.

Our addition of vibrotactile feedback to this system enables quick, simple verification of the system's performance in closed-loop settings. Unfortunately, stimulation artifacts from the transcutaneous electrotactile feedback corrupt the EMG recordings resulting in poor decoder performance. Having the option to complete tasks with vibrotactile feedback enabled us to test closed-loop control without implanted neural arrays.

Due to a combination of the weight of the LUKE Arm and discomfort from the universal socket, the participant was not able to complete as many trials of the fragile egg task as we had originally planned. Although no statistical difference was found when completing the task with sensory feedback versus without sensory feedback for the present limited number of trials, the participant commented on the difficulty without sensory feedback: "when you're doing it without [sensory feedback, you rely] most on vision." The benefits of having sensory feedback in a prosthesis are already well established [3], [4], [11]; our main purpose in completing the fragile egg test here was to demonstrate a working closed-loop system.

The GUI we developed provides much more flexibility for using the system than did our previous system [6], and is more end-user friendly. Whereas we were previously limited to adjusting the system with morse-code-like use of a single button, the GUI allows the user to adjust the system instantly and with greater precision, precluding the need for memorizing a complex set of button presses. The GUI will make the system much more approachable for use in the take-home trial.

The overall system still completes the runtime loop well under the 33-ms loop time, providing real-time movement and sensory feedback below perceivable delay. The system acquires and saves a lot of data during this loop: EMG, decode kinematics, position and force sensor readings from the prosthesis, stimulation frequency and amplitude, and any events from the GUI. The high temporal resolution of the dataset we collect will provide a great opportunity for understanding how an advanced, neuromyoelectric prosthesis is used in the home.

Conclusion

Closed-loop control of an intuitive, multi-degree-of-freedom prosthesis could help persons with limb loss to feel whole again. In this work, we described a portable system that provides six-degree-of-freedom independent, continuous control of the LUKE Arm and uses sensors in the prosthesis to provide biomimetic electrical and vibrotactile feedback. This system provides the foundation for showing the benefits of closed-loop control during unsupervised home use.

Acknowledgment

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Contributions

MDP developed the system's software, GUIs, and ran the experiments. TSD developed the system's software and GUIs. TNT assisted in developing the system's software, GUIs, and running the experiments. MRB provided guidance during the early software development for the system. GAC oversaw all aspects of the research.

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