A PORTABLE MYOELECTRIC PATTERN RECOGNITION-DRIVEN VIRTUAL TRAINING SYSTEM FOR PHANTOM LIMB PAIN MANAGEMENT

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ABSTRACT

Individuals with limb absence commonly suffer from phantom limb pain (PLP), a debilitating condition with poorly understood mechanisms and limited treatment options. Current approaches to treat PLP have broadly proven unsafe or ineffective, leaving patients searching for alternative, long-term options. Recent studies have demonstrated the potential of phantom motor execution therapy, aided by myoelectric pattern recognition software and virtual reality systems, in alleviating PLP. However, widespread clinical adoption has been hindered by limited accessibility, especially for the lower limb absent population. This paper presents the design and development of a portable, myoelectric pattern recognition–driven virtual training system, tailored for at-home use by individuals with upper or lower limb absence to safely and effectively manage and reduce PLP.

INTRODUCTION

Phantom limb pain (PLP) can present a significant challenge for individuals with upper or lower limb absence, with a notable impact on their quality of life. PLP often manifests as sensations of discomfort or pain in the missing limb despite its physical absence highlighting the complex nature of this phenomenon. PLP affects a considerable proportion of the limb absent population, with approximately 79.9% reporting symptoms, among which 38.9% rate the pain as severe [1]. Symptoms of PLP can occur immediately after amputation and often remain during chronic stages of recovery, emphasizing the need for effective treatment options that can alleviate or help manage PLP long-term.

Current treatment approaches for PLP often involve pharmacological or surgical interventions, which may carry risks or prove ineffective for some individuals [2]. Non-invasive therapies, such as motor imagery and mirror therapy, provide safer alternative treatment. These neuroplasticity-based approaches ultimately aim to restore normative brain circuitry to alleviate pain. While both techniques activate similar brain regions, mirror therapy has shown greater effectiveness, likely due to the requirement for patients to activate different muscle groups in the residual limb, instead of mentally simulating movement of their phantom limb [3, 4]. Active engagement of residual limb muscles could possibly explain why regular use of a prosthesis has also shown to help reduce PLP [5, 6].

Most modern upper limb prostheses use muscle activity measured from residual limb muscles to control motorized arm components. Advanced myoelectric-controlled prostheses employ machine learning algorithms, such as pattern recognition, to decode the user's muscle activity patterns, enabling more intuitive control of their prosthesis. Recently, researchers have proposed a more advanced approach to mirror therapy that leverages pattern recognition technology to better capture, and perhaps, enhance user engagement by combining it with virtual reality systems. Such systems offer a more dynamic and immersive platform for individuals to actively engage movements that mimic those of their missing limb, termed phantom motor execution therapy. While myoelectric-controlled virtual reality systems have shown promise for PLP management [7], its widespread clinical implementation has remained limited, particularly for the lower limb absent population which has a higher prevalence of PLP [8].

This paper describes the design of a portable myoelectric, pattern recognition-driven virtual training system, referred to as the Phantom Limb Pain Management System (PLP-MS), which is suitable for individuals with either upper or lower limb absence who have chronic PLP. The PLP-MS consists of an expandable EMG-embedded cuff worn on the residual limb and a cloud-connected mobile software application featuring interactive virtual games played using phantom motor execution. With an aim to provide an accessible and effective treatment solution, the

PLP-MS provides users the flexibility to manage PLP virtually anywhere and as needed. Another key feature is its integration into a connected health platform, enabling remote delivery and monitoring of device training and therapy and thus facilitating a telerehabilitation application for PLP management.

HARDWARE DESIGN

EMG-embedded cuff: The main mechanical component of the PLP-MS includes a semi-rigid and expandable electrode-embedded arm/leg cuff (Figure 1). The cuff was made to fit comfortably with two different size options to accommodate most residual limb sizes. The standard-sized cuff has a minimum circumference of 17 cm (a cross-arm diameter of 5.4 cm) and maximum circumference of ~35 cm when fully expanded. It is suitable for upper residual limbs (above- or below-elbow) and fits most below-knee residual limbs. A larger version of the cuff has a minimum circumference approximately the maximum circumference of the standard-size cuff and can fit residual limb sizes up to ~60 cm.

Fig. 1: A standard and larger sized EMG-embedded arm/leg cuff embedded with bi-polar electrode sensors for convenient acquisition of up to 8 muscle activity signals.

Both sized cuffs were designed using CAD software and fabricated with 3D printed material. The cuffs comprise of 9 pods (8 EMG sensor pods and 1 main pod) which are adjoined radially by linkages attached to each pod. The linkages have a novel hinge mechanism to allow the cuff to expand when donned on the residual limb. For the larger-sized cuff, the linkages were made thicker which effectively increases the distance between the pods when not expanded.

Each of the EMG pods has two dome-shaped electrode sensors (one on each end, spaced 5 cm apart) such that 2 bands of 8 electrodes are equally spaced around the inner part of the cuff. A reference/ground electrode is in the middle of the main pod. Connection wires transmitting the EMG signals to the signal processing unit housed inside the main pod run along inner channels of the linkages. Enclosed on the face of each EMG pod are colored LED lights that illuminate at different intensities based on the underlying EMG muscle amplitude.

Controller Hardware: The main pod of the cuff houses the necessary hardware for amplifying and digitizing EMG signals and a microcontroller to translate recorded EMG signals into motion output commands using pattern recognition. This control system features enhanced digital filtering for optimal EMG signal quality, Bluetooth Low Energy communication, expandable data storage capacity, and power management and USB-C fast charging capabilities, among other functionalities. The charging circuitry, compatible with a 3.7V lithium-ion battery, includes undervoltage detection to safeguard against battery depletion below 3V. To ensure user safety, the power management circuitry disengages the system load during battery charging, preventing any risk of exposure to mains voltage from the USB-C port. The top of the main pod features a power button accompanied by a light indicator to convey power status, charging progress, and low battery notifications.

SOFTWARE DESIGN

Pattern recognition: The PLP-MS controller performs on-board signal processing and translates recorded EMG signals into motion output commands using an adaptive pattern recognition control algorithm [9]. Users are required to train (i.e., calibrate) the system by inputting representative EMG data for each selected limb motion to control. Users can train the system at any time to improve and personalize controller performance.

Mobile App Software: The PLP-MS controller communicates wirelessly via Bluetooth Low Energy to a custom interactive and user-friendly mobile application, called Control Companion™ (Figure 2). The mobile app was developed in Unity and is available on both iOS and Android platforms. It is compatible with Coapt's commercial Complete Control Gen2 pattern recognition system developed for controlling upper limb powered devices. Compatibility with the PLP-MS required some modifications such as adding lower-limb specific configuration elements. The controller streams recorded EMG signals and motion output commands to the mobile app. The main environments in Control Companion™ include:

Myoexplorer: A visualization tool that allows users to view their muscle activity in real-time using color-coded and dynamic representations of the EMG amplitudes recorded by the sensors (Figure 2, left). Myoexplorer can be used as a training tool to help visualize similarities and differences between muscle activity patterns corresponding to each motion and to explore the virtual space to train new patterns.

Configuration: Users can configure their controller according to limb loss side (right/left) and level (below- or above-elbow and below- or above-knee) and select the limb motions they want to train and use while playing virtual games (Figure 2, middle). Available motions include hand open/close, wrist supination/pronation and elbow flexion/extension for the upper limb users and ankle inversion/eversion, ankle flexion/extension and knee flexion/extension for the lower limb users.

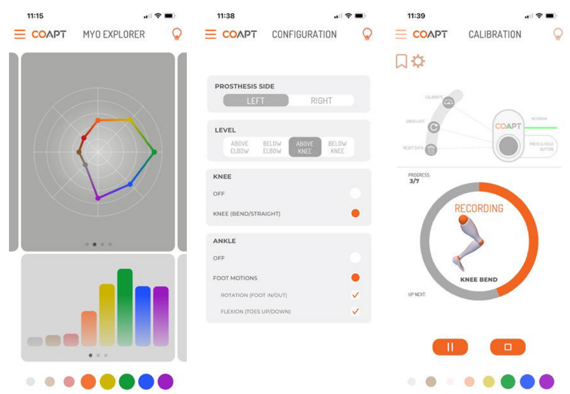

Fig. 2: The Control Companion™ mobile app allows users to view their EMG signals (left), configure the controller (middle) and calibrate selected limb motions (right).

Calibration: Virtual limb animations guide users through a motion calibration sequence to train their pattern recognition control system for each selected limb motion (Figure 2, right). Alternatively, users can also add additional EMG input data to any individual motion. Feedback about the quality of their calibration data and suggestions for improvement are provided through the AI-driven Control Coach® [10].

Training and Games: The app includes a range of virtual training and practice games (Figure 3) which are tailored to the user's limb loss level and side using custom virtual limbs and icons to prompt them to perform specific limb motions during gameplay. Simon Says tests their ability to isolate individual motions by requiring them to control the movement of a virtual limb until it matches a target position (Figure 3A). In-the-Zone tests their ability to modulate their muscle contraction intensity using proportional control by requiring users to match and hold their contraction intensity to a target level (Figure 3B). Zap It tests their ability to perform a sequence of prompted motions (Figure 3C). Each of these games allow users to select their preferred difficulty level (Beginner, Intermediate, Advanced) which changes game parameters (e.g., size of target, amount of time to hold in target) to make them more challenging and game performance metrics are displayed on the screen upon game completion. Additional games offer users greater freedom, such as Paper Flyer where they can hone their movement coordination skills by controlling the flight path of a paper airplane along two axes, navigating it through virtual rings (Figure 3D), Flick It Golf where they command motions to aim and shoot a ball into a hole, avoiding or using virtual objects to their advantage (Figure 3E), and Raceway where they navigate a car through an obstacle course trying to capture objects that provide a boost (Figure 3F).

Pain Assessment Tools: Interactive clinical tools allow for convenient collection of user-reported pain ratings. These include a Numerical Pain Rating Scale where users are prompted to rate their PLP on a standard 11-point scale (0 – no pain to 10 – very severe) (Figure 3G) and a Visual Analog Scale where users are prompted to move a slider on a vertical scale from "Zero Pain" to "Most Pain" (Figure 3H). The tools can be accessed at any time or pre-set to be presented to users at specific time intervals (e.g., every 24 hours).

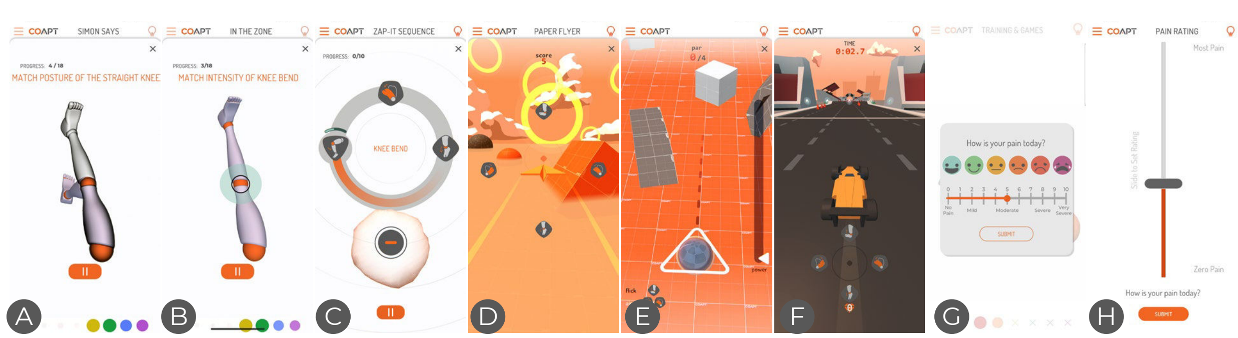

Fig. 3: The Control Companion™ mobile app offers a variety of virtual games and self-report pain rating tools.

Cloud-Connected Software: The Control Companion™ mobile app has cloud-connected data storage capabilities to remotely record a wide range of user data from connected devices; including calibration data, virtual game data and self-reported pain scores. Data is uploaded to a HIPAA-compliant cloud storage database hosted on Microsoft Azure Cloud Platform. Integration into a Connected Health Platform offers a convenient resource for researchers and clinicians to monitor device use and diagnostic information and to track user performance. User data can be viewed in a web-based software application containing real-time EMG signals, virtual game performance and aggregated data insights.

CLINICAL IMPLEMENTATION

Development of the PLP-MS was performed under a rigorous design process with clearly defined user and device specifications and testing procedures. This included gathering user and clinician feedback on hardware and software components in collaboration with the Shirly Ryan AbilityLab (Chicago, IL) who completed in-lab pilot usability and functionality testing with limb absent subjects (Figure 4). Feedback was used to iteratively refine and improve the PLP-MS prior to deployment for an ongoing at-home clinical trial evaluating its efficacy in reducing pain across 48 upper and lower extremity patients.

Fig. 4: A below knee (left) and above knee (right) limb absent subjects donning an cuff and playing virtual games.

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