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Robotic Therapy for Phantom Limb Pain in Upper Limb Amputees

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***Abstract*— Advances associated in terms of cost and quality in virtual reality have brought new paradigms to help with rehabilitation in a vast range of areas. Previous systems have focused on visual based only paradigms with varied results. The system described in this paper draw not only from visual based approaches but also adding elements of haptics to increase the level of immersion but in combination also invoke the sense of agency in patients with phantom limb pain. This paper presents three case studies of an on-going clinical study. The initial results suggest an increased sense of embodiment of the virtual limb promotes a decrease in perceived levels of pain. The results strengthen the view that the cortical map does not fully "disappear" yet lays dormant.**

I. Introduction

The decision as to whether to attempt limb salvage or an amputation is difficult but in either case there are subsequent problems with rehabilitation including phantom pain and limb non-use[1]. Phantom limb phenomenon affects a large percentage of amputees (50-80%) and results in feeling body parts that are no longer there[2]. Amputated limbs can ache, itch, burn, feel dry or wet, tense, locked or stuck, or even feel they are moving[2], [3].

The effects of Phantom Limb Pain (PLP) can worsen due to anxiety/stress and other factors[2]. Not only does this affect the individual's mental wellbeing (coping with the psychological trauma associated with the limb loss) but also their physical state (imposed by the chronic pain effects) and the rehabilitation outcome[4]. Regional rehabilitation units, Defence Medical Rehabilitation Centres and NHS rehabilitation centres are posed with diverse challenges as the individual experiences emotional discomfort in addition to psychological trauma, reduced mobility and Phantom Limb Pain[5].

One treatment option available is mirror box therapy, which has been shown to have an effect in some amputees in reducing PLP[6], [7], however this tends to result in short term relive[8], [9]. It is believed this is due to the amputee embodying the visual mirror image of their intact limb where their amputated limb is located. One method of enhancing embodiment of a visual surrogate is to employ tactile feedback which has been shown to reinforce embodiment of a visual image within both the amputated and non-amputated population[10]-[12] and thus more longer periods of relive. Which has lead to research in using TMS to provide targeted feedback back to the CNS to allow amputees to feel objects they are holding onto with their prosthetic limb[13].

Our on-going clinical pilot study taking place at the Royal National Orthopedic Hospital, Stanmore and other partner sites, aims to establish a more solid scientific framework for advancing the knowledge of haptic interaction in the treatment of Phantom Limb Pain and its outcome will be used to inform a future phase II trial to quantify the new approach in terms of cost benefit and therapeutic practice. In this paper we present a robotic system that facilitates retraining of simple manipulation tasks by amputees and initial results from our on-going clinical trial.

II. Methodology

A. The system

Motor tasks are performed using an immersive haptic sensorimotor training system (Fig. 1) that provides, direct physical contact to a haptic robot, mapping of the information from the robot to the virtual representation of the physical limb, and an application that maintains challenge and interest to the individual. Based on these elements, the system acquires EMG commands, residual limb kinematics and displays the combined residual limb movements in a virtual reality environment that includes force-based interactions with virtual objects. Visualisation is provided via a Head Mounted Display so as to facilitate first-person view of the virtual environment and embodiment of the residual limb with the virtual representation[14], [15]. The

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Unreal Engine 4 is used to render the exercises together with custom software that synchronises the control loops and communication with the different subsystems.

The participant is connected via a residual limb interface (gimbal) to the haptic robot (HapticMaster), which provides limb tracking in 6-dof (position and orientation) and force feedback in 3-dof. A Primesense camera with supplemental Nimble [16] camera hand tracking system is placed on the table via a flexible stand to track the participant's intact hand. The haptic robot has two purposes; 1) to support and track the amputated limb's movement and 2) to provide haptic feedback. The residual limb interface can be customised to fit different stump sizes.

Fig.1 Typical set up of the system in a right handed configuration showing a participant connected to the 6dof robot. Top left image shows the participant's view of an exercise.

Position and orientation data from the gimbal of the haptic robot and Nimble camera is fed into a custom made inverse kinematic solver which produces the correct anatomic position and orientation for a virtual avatar upper limb being controlled by the participant. The benefit of using a pure immersive VR approach is that scaling up the movement of the virtual limb being controlled via the participant becomes straightforward.

Haptic effects are applied in such way to simulate different object weight properties, collisions on impact with other objects and textures of various materials that a participant could interact with. The haptic layer of the system is separate from the visual layer with communication between a custom made HapticMaster plugin in Unreal Engine 4 and a haptics server via TCP protocol.

The Oculus Rift HMD (DK2 version) is used to provide a stereoscopic first person view of the virtual environment collocated with an avatar head and body position. The Nimble camera hand tracking system tracks the participant's intact hand not connected to the haptic robot. Due to the unilateral exercises, the intact limb used to start the exercises and to provide the participant with control over the exercises by placing the virtual intact limb onto a green rectangle placed on a table in the virtually environment. The decision to use this type of virtual control over a more physical control was due to efforts ensuring that the immersion of the exercises was not broken during the sessions.

EMG sensors are placed on participant's suitable residual muscles. A training session is carried out to extract and classify muscle features to be mapped to a binary open/close of the virtual hand of the avatar. A TMSi Porti amplifier is used to collect all physiological sensors at 1024Hz. In order to identify grasp and release training data is classified using OpenVibe[17]; a LDA classifier is used in a custom made OpenVibe script which takes all the physiological data channels, correctly segregating the channels (EMG, Galvanic Skin Response and respiration) before sending the raw and classified data to the Unreal Engine 4 system via the VRPN protocol[18] and a small python script. The VRPN signal sent to Unreal Engine 4 is only a binary value, however different kinds of grasp can be selected for each exercise.

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Other physiological sensors such as GSR sensors placed on the fingers of the intact hand and a respiration sensor placed underneath the nose with probes in front of the mouth and in the nostrils, are used to gather the secondary measures, following the same data flow as mentioned above.

The system has been designed to log all data per exercise as csv files to be preprocessed and analysed at a further date within the correct participant information automatically via a drop down menu filled in at the start of the session.

The system acts as a decoupled version of the mirror box therapy adding in the sense of agency in that the participant is not only seeing (via the Oculus Rift) the correct position and orientation that their phantom limb (via the virtual limb), but that they are controlling the reaching and grasping movements (via the EMG electrodes placed within the residual muscles of the amputated limb) and physically interacting with the virtual objects.

Fig.2 Top row of images shows 4 exercise areas with the bottom images showing the participant view point of those exercises.

Several ADL exercises have been developed (Fig.2) for the participant to undertake during the therapy sessions. These include:

1. An exercise inspired by the blocks and box test.
2. A cleaning exercise in which the participant is tasked with grasping an eraser and using it to clean a painting filled with dust.
3. A shopping exercise in which the virtual avatar is placed in front of a conveyer belt with moving items. The task involves the participant reaching to grasp objects and placing them in a basket in front of the virtual avatar.
4. A restaurant scene in which the participant picks and places objects such as dishes, glasses, forks and knives onto a tray.
5. Juice making task carried out by picking fruit from a tree and placing the fruit into a juicer.

C. *Clinical Study*

1) *Methods*

A total of 20 participants are being recruited to the study. Participants are placed into one of two groups, a control group (visual surrogate for the missing limb without the force feedback) and an experimental group (visual surrogate for the missing limb with force feedback). The study was approved by the NHS ethical committee and is on the NIHR portfolio. This paper presents the initial results obtained with three case studies recruited to the on-going study for the RNOH Stanmore cohort (Mean age – 50.3 Mean time since amputation – 12.3 years, SD 21.54) who have fully completed the robotic intervention and follow up assessments. An overview of the participants can be found in (Table. 1).

2) *Participants*

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Participant ID	Gender	Age	Amputation Side	Amputation Level	Time since Amputation	Prosthesis Used	Onset PLP	Medication	Group
RNOH2	Male	58	Right	Transhumeral	30 years	Cosmetic	Since operation	Yes	VR
RNOH3	Male	26	Right	Transhumeral	1 year	Cosmetic	6-7 months post operation	No	VR & Haptics
RNOH4	Male	67	Left	Transhumeral	6 years	None	Since operation	Yes	VR & Haptics

Table 1. Participant Summary

RNOH2 is a 58-year-old male assigned to the control group who via an accident lost his right arm and leg over 30 years ago. Immediately after the accident he had his right arm amputated above the elbow. He experienced PLP straight after the operation and had been on medication (Pregabalin & Gabapentin) ever since. This participant has been a prosthesis user since the operation (dominant hand was his left side) and has used the same body powered prosthesis since his operation.

RNOH3 is a 26-year-old male assigned to the experimental group who lost his right arm (also his dominant side) via a motorbike accident over 2 years ago. An above the elbow amputee in which the onset of PLP started a year after the amputation. This participant did not take any medication for the pain and has been using a cosmetic prosthesis since the amputation.

RNOH4 is a 67-year-old male above elbow amputee assigned to the experimental group who lost his left arm via an accident 10 years ago. Onset of PLP was instantly post amputation and he has been on medication for the pain ever since (Pregabalin & Gabapentin). This participant is a non prosthesis user, however due to the level of amputation and the set up of the equipment a cosmetic prosthesis was made to be worn for the duration of sessions. His dominant side is his right side.

3) Measures

Physiological sensor information is used to quantify psychophysiological responses to the audio-visual and haptic cues provided by the system. Perception of the environment (and from the haptic cues) invoke proprioceptive and exteroceptive user responses that result in motor actions and a subsequent response (e.g. movement of the limb, feeling the weight of an object). Possible motor control actions are picked up by a range of different biomechanical sensors (present in the haptic device), by the HMD (head tracking) and kinematic tracking of the residual (and intact) limb. A series of outcome measures assessing changes in reported pain, embodiment, psychophysiological responses, muscle activation, kinematics features and qualitative information in the form of a diary, are used to quantify therapy effectiveness.

In this paper we report on the perceived pain and embodiment measures:

- McGill pain (short) questionnaire: was used to measure perceived levels of pain experienced by the participant taken at the beginning of the study, at the end of each therapy session and at a follow up session.
- Botvinick's embodiment questionnaire[19]: was used to measure perceived levels of embodiment (limb ownership) that the participant may experience, which is taken at the end of each session.
- Proprioceptive drift estimation: was used to measure the perceived level of embodiment before and after the intervention session. This measure consists of taking the distance the participant perceives their limb has moved. Two measurements (participant points to where they think the center of their hand is) are taken one before and another after the exposed immersion (before/after each session). The difference is produced and used as the measure of proprioceptive drift.
- Pain diary: participants were asked to keep a pain diary for the length of the study until final follow up.

4) Data Collection & Analysis

Both internal UE4 data (information about the virtual avatar and other level specific objects) along with external data such as raw EMG data and kinematic/kinetic data from the HapticMaster are synchronised and saved in a text file for offline processing.

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It is anticipated that if the hypothesis is supported, significant larger effects (higher pain reduction and increased embodiment levels) will be observed on the VR + Haptics group when compared to the VR only group. This initial analysis will also allow us to observe any temporal effects on pain and embodiment. We estimate a higher temporal effect (e.g. steeper slopes earlier) with the VR + Haptics group.
We acknowledge that the effect of novelty (just the fact of someone being involved in the trial) might have an impact on the results.

E Study Timeline

Participants had an initial meeting (Fig.3) in which the study was further explained and consent was taken. This was followed later by a preparation session used to set up the sensors and conduct EMG pattern recognition for each participant. An initial pain questionnaire was also taken along with allocation of a pain diary.

The subsequent three weeks involved nine sessions (1 hour each) spread evenly. The proprioceptive drift is taken before and after the session, short McGill and Embodiment questionnaires are taken at the end and all sensor/kimematic/kinectic data is automatically collected during the session. For each session one hour is used for performing the exercises with the robot.

After three weeks of intervention a post intervention period of three weeks followed in which no further intervention with the robot took place.

Finally, two follow up sessions six and twelve weeks since study start are conducted where a short interview were conducted along with short McGill and proprioceptive drift measurements.

Fig.3 Flowchart showing the study time line.

III. Results

A. Overview

Overall no negative side effects in terms of pain are reported. Further analysis is required on the kinematic data, therefore the focus will turn to the McGill Pain (supplemented by the participant's pain diary) & our modified embodiment questionnaire along with the proprioceptive drift measurements. The McGill pain questionnaire is scored from 0-5 (0 being no pain). The embodiment questionnaire uses a likert-type scale from 1 (strong disagree) to 7 (strongly agree). Question 3 will be presented only due to the general nature of the question "I felt as if the virtual limb were my (real) limb.". In terms of proprioceptive drift the majority of the reported participants in this paper show a trend of decreasing error in distance taken from post intervention measurement minus pre intervention measurement. In contrast with the majority of reported proprioceptive drift measurements in the literature, the results presented in this paper take into consideration both the X & Y coordinates not just a single axis. This was done to make the results as accurate as possible.

B. Case study I - RNOH2

As shown (Fig.4), for RNOH2 there does seem to be an initial correlation in terms of increased embodiment and a decreased level of reported pain from sessions 1-6. With a one point score increase from session 6 to session 9 however ending the sessions with less pain than the baseline pain score. Although there is an increase in pain between the first and second follow up sessions the participant noted that other factors have contributed to this increase. The participant reported in their pain diary that for a week and a half from the end of the sessions there was little or no pain (score < 1). This participant was placed within the control group (VR only) and uses prosthesis. Interestingly the participant noted that it took some time for him to believe that it was himself

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controlling and opening and closing of the virtual hand via EMG, this could explain the jump in embodiment towards the 4th session. Examining RNOH2's pain diary the levels of pain during the intervention period of 3 weeks during the intervention the average pain recorded by the participant was 1.9/5 (Standard deviation 0.98) whilst post intervention the average pain recorded was 2.9/5 (Standard deviation 1.27) .

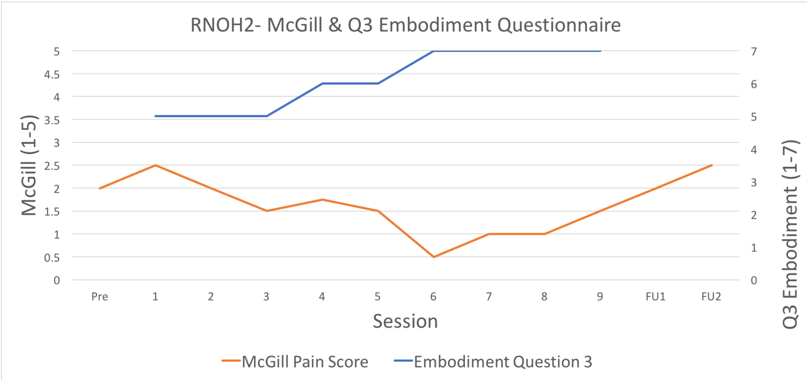

Fig.4 Plot showing both the McGill pain score in orange (0-5) and question 3 of the embodiment questionnaire in blue (1-7) from baseline through to the 2nd follow up session for participant RNOH2.

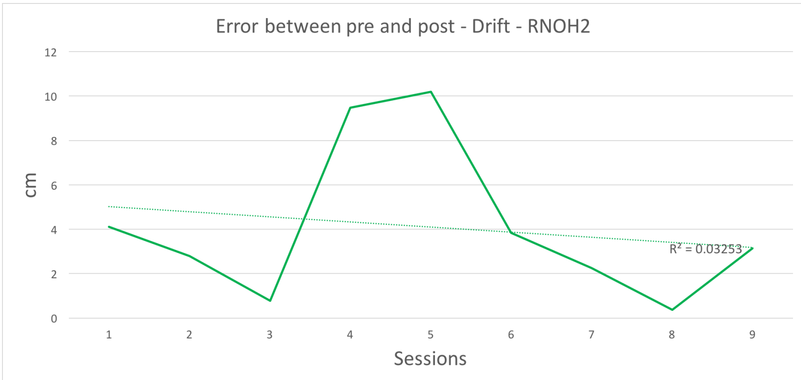

Fig.5 Plot showing the error in cm between drift measurements taken pre and post session during the 9 intervention sessions for participant RNOH2.

RNOH2's proprioceptive drift error (Fig.5) does generally suggest a decrease (linear $R^2 = 0.03253$) despite an approx. 9cm jump increase from sessions 3 to 4. However, this could be explained due to the fact that 3 sessions were scheduled a week with a 4 day gap between the 3rd and 4th sessions for this participant. With most of the error being 4cm or less between the start and end of the intervention sessions.

C. *Case study II - RNOH3*

RNOH3 who is a prosthesis user was placed in the experimental group (VR + Haptics) out of the three participants reported in this paper experienced the best outcome in terms of pain levels. As shown by (Fig.6), by the 3rd session there was no pain reported even at the final follow up session. Despite the elimination of pain during the intervention there was 12 self reported instances of pain (average of 2/5 Standard deviation 1.42) written in the pain diary post intervention.

However these episodes of pain were reported to last seconds to the maximum of 10 mins. The participant reported that he was able to get the pain to go away quickly employing tactics such as distraction or imagining performing the one of the exercises during the intervention. The participant was a recent amputee (approx. 1 year), which might account for the effectiveness of the

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intervention. Despite a dip in the level of embodiment in session 2 there seems to be a strong link between embodiment and the perceived levels of pain reported.

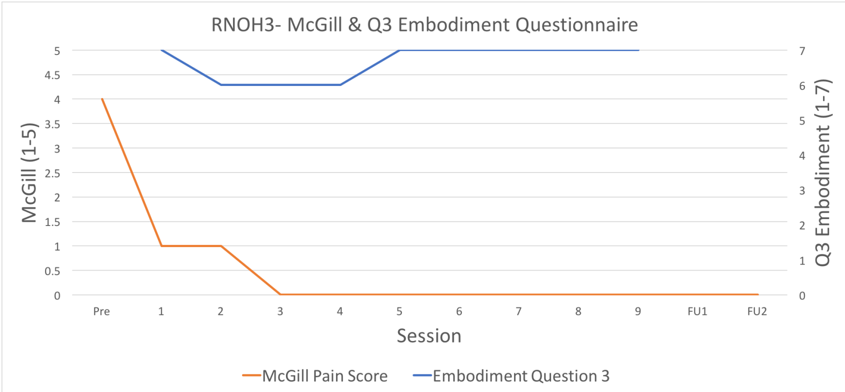

Fig.6 McGill score and embodiment question graph for participant RNOH3.

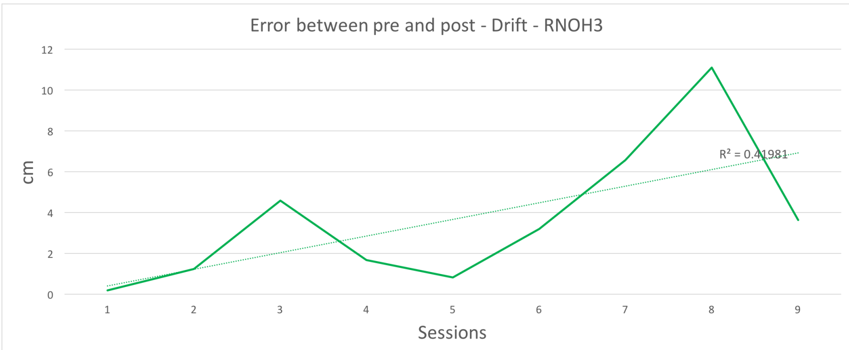

Fig.7 Drift error graph for participant RNOH3.

RNOH3's proprioceptive drift error (Fig.7) remained fairly low to session 6 (similarly to RNOH2's < 4cm, average 1.9cm error) Standard deviation 4.56 with an 4.54cm increase in error during sessions 7 and 8. One possible reason for this could be due to the fact that sessions 6 and 7 were held on the same day with session 8 being held the day after, fatigue may be behind this increase in error despite the embodiment questionnaire suggesting otherwise. This resulted in an increase trend (linear $R^2 =$ 0.41981) in error during the sessions.

D. Case study III - RNOH4

RNOH4 who did not use a prosthesis and had one made for the clinical study, and was also placed on the experimental group (VR + Haptics). Interestingly, unlike the two previous case studies presented in this paper there is little to no link between embodiment and reported levels of perceived pain (Fig.8). The lack of embodiment and fluctuation of pain levels might be attributed to the participant's non-usage of a prosthetic limb. Despite this fluctuation we also suggest that a longer period of intervention might raise the level of embodiment and thus lower the perceived levels of pain. As noted in the RNOH4's pain diary, reduced pain levels in general were reported from just before the 7th session. This further reinforces our suggestion that longer intervention for this particular participant would be beneficial. In addition, we also extracted from the pain diary the average pain during intervention (2.9/5, Standard deviation) and post intervention (2.8/5 Standard deviation) but also an average decrease in the time the pain was present as recorded by the participant; approx. 20 minutes per day on average during the intervention period vs. approx. 9 minutes per day on average post intervention, a decrease of approx. 11 minutes.

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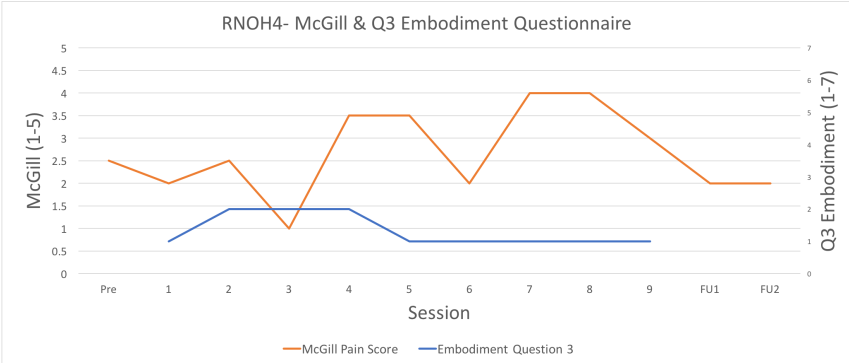

Fig.8 McGill *score and embodiment question graph for participant RNOH4.*

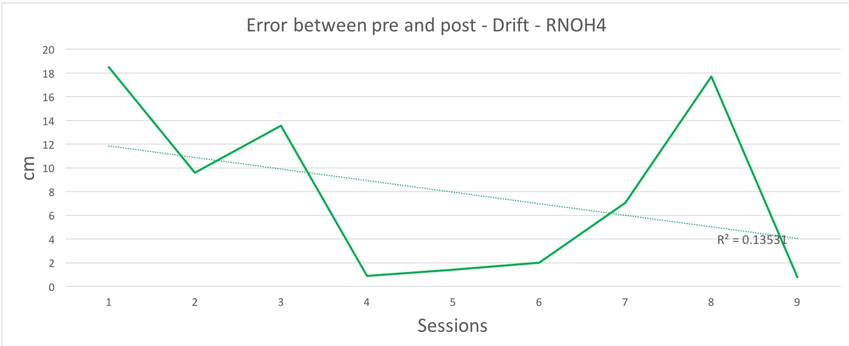

Fig.9 Drift error graph for participant RNOH4.

Interestingly although RNOH4 did not show much embodiment via the embodiment questionnaire the proprioceptive drift error results (Fig.9) do generally tell another story. That is, a sharp decrease can be observed up to session 4, with only a minor increase between sessions 4 and 6. However, a 15.71cm increase in error between sessions 6 and 8 followed by a 16.92 decrease in error for the final session can be noted. With this taken into consideration a decreasing trend line (linear $R^2 = 0.13531$). Although the drift error does not correspond to the qualitative embodiment measure it does explain the reduced level of perceived pain mentioned in this participant's pain diary.

IV. Conclusion

This paper has outlined our novel system in combining VR and haptics to aid in the reduction of Phantom Limb Pain. Initial results presented with the reported three case studies seem to support our design goals, in that the system is used to strengthen the participants' embodiment of a virtual limb by exposing the sense of agency coupled with haptic effects in lowering perceived levels of pain. The link between embodiment and pain for the majority of these cases does suggest a correlation.

The initial results seem to suggest lower levels of perceived pain as a result of exposure to the intervention. Although no firm conclusion can be drawn from three case studies, it appears that the sense of agency rather than embodiment could possibly be a larger factor in pain reduction than thought before.

Based on our initial results, one trend seems to be emerging – amputees who are either recent amputees (prosthesis or non prosthesis users) or long-term amputees who are regular prosthesis users, might experience larger pain reduction benefits.

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