MetaArms: Body Remapping Using Feet-Controlled Artificial Arms

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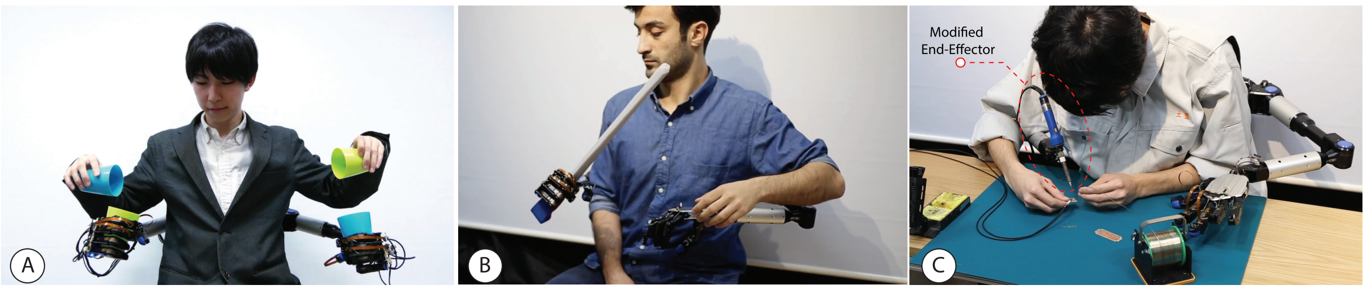

Figure 1. MetaArms allows expanding the number of upper limbs by remapping the user's legs to new artificial limbs: A) Users can experience four fully-independent arms that can facilitate tasks difficult to be achieved without an extra pair of hands; B) User's attention is directed towards the new arms rather than the operating limbs (i.e. legs); and C) The artificial limbs can be customized to perform new functions.

ABSTRACT
We introduce MetaArms, wearable anthropomorphic robotic arms and hands with six degrees of freedom operated by the user's legs and feet. Our overall research goal is to re-imagine what our bodies can do with the aid of wearable robotics using a body-remapping approach. To this end, we present an initial exploratory case study. MetaArms' two robotic arms are controlled by the user's feet motion, and the robotic hands can grip objects according to the user's toes bending. Haptic feedback is also presented on the user's feet that correlate with the touched objects on the robotic hands, creating a closed-loop system. We present formal and informal evaluations of the system, the former using a 2D pointing task according to Fitts' Law. The overall throughput for 12 users of the system is reported as 1.01 bits/s (std 0.39). We also present informal feedback from over 230 users. We find that MetaArms demonstrate the feasibility of body-remapping approach in designing robotic limbs that may help us re-imagine what the human body could do.

CCS Concepts
•**Human-centered computing** → **Interaction devices;**

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Artificial Limbs; Feet Interactions;Body Remapping; Body Schema; Fitts' Law; Augmented Arms; Human Enhancement.

INTRODUCTION
The human body is inherently constrained by its physical structure that imposes some limits on the functions the body can perform. Such physical structure is reflected in the mental model of our body (i.e. body schema) that can be temporarily changed by using tools and devices [16, 26, 3], while enhancing our body functions beyond the inherent limits. Both wearable computing and wearable robotics have been experimenting with ways to go beyond such human limits with different emphases.

Today's wearable computing devices are mostly statically worn on a particular body part with relatively conservative input and output modalities (e.g. visual, audio, and limited haptics). Wearable robotics, on the other hand, has largely focused on assistive or rehabilitative functions, such as an exoskeleton that helps a user lift heavy items [47] or specialized robotic limbs that support humans in performing specific tasks [31, 30]. In both areas, however, the ease and intuitiveness of system operation and subjective sense of embodiment remain a challenge. In our research, we endeavor to expand on such "wearable" technology to try and create a system that feels more like an integral part of our body and augments our human capabilities, moving from human-computer interaction towards human-computer integration.

Towards this end, we adopt a "body-remapping" approach. This is in part inspired by the neurology research that shows we can transfer learned motor skills between different body parts [37]. We present a system that demonstrates how technology can be used to remap parts of our body with relative ease to provide not simply augmenting functions but also create a room for re-imagining how we may use our body. We present a first exploratory case study in which we propose mapping the movements of the lower limbs to the upper limbs. MetaArms are additional anthropomorphic robotic arms worn on the back and controlled by the user's foot motion. Figure 1 shows an overview of the proposed system and how these arms are operated in coordination with the user's leg and foot motion. Further details of the proposed interaction are discussed in the Approach section.

This work's main contribution is the introduction of a new approach to robotic limbs research that remaps lower limbs onto the artificial arms/hands, using feet both for motion input and feedback output. We have conducted a preliminary testing of the interaction's validity, using a 2D pointing task following Fitts' Law (ISO 9241-9), as well as through informal observation of more than 230 users as they tried out the system at three different events. In the Fitts' Law test, the system achieved a mean throughput of 1.01bits/s (std 0.39) among 12 users.

RELATED WORKS

Our work draws from and is inspired by a diverse research corpus. In this section, we focus on these most relevant areas: augmented limbs (both for substitution and expansion) and feet interactions in HCI.

Augmented Limbs

Robotic limb research has, for a large part, focused on the prosthesis or industrial applications to increase strength or similar human parameters [17, 9, 20, 6]. There is a large body of studies that covers augmented arms, hands, and fingers, and among them are some notable studies on enhancing human capability by adding extra limbs to the human body. Stelarc's Third Hand [18, 38] was one of the earliest art performances that investigated the effect of adding a third hand to augment bodily functions. The hand was controlled by a set of electromyography (EMG) sensors attached to his body, requiring him years of training to adapt using the hand effectively [8].

More recently, Parietti et al. proposed Supernumerary Robotic Limbs (SRL): wearable robotic arms that supported the user in performing specific tasks, such as machine assembly [31, 30]. Non-actuated robotic arms were installed on the user's hip and assisted the user by holding objects or fixing the user's posture. In another example of robotic arms worn on the body, Bonilla and Asada presented a design concept of augmented arms on the shoulders [4]. Vatsal et al. proposed another wearable limb with a twist, implementing an additional hand attached to the forearm [41].

There are some notable works that explored the possibility of adding extra fingers as well. Prattichizzo et al. proposed The Sixth-Finger, a modular robotic sixth finger to increase hand dexterity and to augment gripping [32]. In a similar vein, Wu and Asada [43, 44] offered Supernumerary Robotic Fingers (SR Fingers), adding two robotic fingers to support tasks that usually require two hands. In addition to the wide body of research on robotic limbs specialized for predetermined tasks, there are also more exploratory works that provide modular robotic platforms to build customizable robotic limbs. Leigh et al. introduced a system of programmable robotic fingers that could provide synergistic interaction through programmable joints [21, 22].

Sasaki et al. provided a similar setup, though their original work was merely conceptual and did not provide an evaluation of their system (neither technical, qualitative nor quantitative) [34].

We believe our work provides a useful and hopefully thought-provoking addition to the wearable robotic limbs research with our focus on "remapping" limbs, which can offer not only possible substitution and augmentation functions but also could create an exploratory space for re-imagining what the human body can do.

Feet Interaction in HCI

There are many traditional studies that use hands for input in HCI to manipulate virtual objects or control the motion of robots with a glove device, etc. [39]. In contrast, there are fewer approaches that use feet for input.

Velloso et al. provide a good summary of interactions with feet [42]. Previous work in feet interaction mainly used conventional pedals to control graphical user interfaces (GUI), but it has more recently expanded to include physical applications such as walking detection or dance performance feedback [12, 36, 45, 7, 11, 29]. In feet interaction research, sensing techniques for detecting foot conditions, acceleration, bending, and pressure are commonly employed. These works have mainly focused on detecting the motion of the foot, and toe movements or bending have not been typically considered.

As for feedback, tactile stimulation to the feet has been already employed, but for relatively limited kind of feedbacks, mainly focused either on notification scenarios or on simulating a walking effect [33, 35]. In order to create a closed-loop interaction between the feet and the user, feedback is necessary to be actively and passively perceived by the user. As the rubber hand illusion [5, 1] shows, coupling haptic feedback with visual feedback can induce a strong sense of ownership toward the artificial hand, which could contribute to more intuitive control.

To our knowledge, no study has been conducted to evaluate the effectiveness of feet control for manipulating a tightly coupled robotic arms system with haptic feedback applied to the feet.

APPROACH

As seen in the previous section, there are already well-established research paradigms for augmenting the human body using external limbs that explore a variety of methods to control the additional limbs. We believe our approach offers a new perspective to the robotic limbs research by focusing on body remapping. MetaArms remap the user's foot-and-toe movements on the robotic arms and hands, and this approach has a few advantages. Chief among them is the relative ease of mastering control of the robotic arms. Although the idea of using the lower limbs to perform the functions of the upper

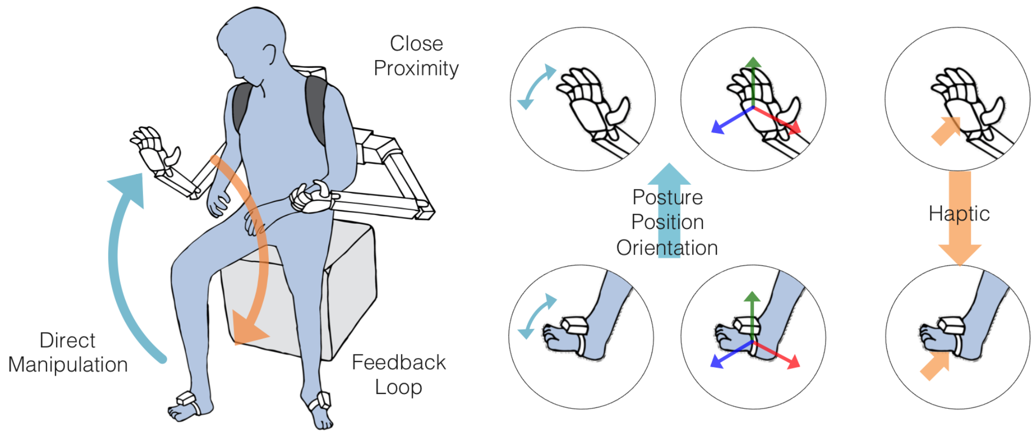

Figure 2. MetaArms design approach: a closely situated anthropomorphic arms system driven by leg and feet motion, with haptic feedback loop.

limbs may not seem "easy" at first, we believe it can potentially allow for more intuitive control, compared to other modalities such as eye gaze and EMG signals. In fact, Spampinato et al. showed that it is possible to transfer motor skills between hand and legs [37]. MetaArms is an attempt to apply the concept of motor-skills transfer to robotic limbs. We found the following design considerations necessary in our first design of the exploratory MetaArms prototype. Figure 2 shows an overview of the designed approach, postural mapping, and feedback loop.

Direct Manipulation

The first design consideration is to give the user control of two additional independent arms/hands for interactions. We considered and prototyped different interaction modalities, ranging from electroencephalography (EEG), eye gaze, and EMG to game controller input. However, each came with substantial limitations (user-dependent training, noise issues, etc.). In addition, we did not want to hinder free movement of the user's own hands, as our aim was not just to substitute the human arms/hands but to extend their capabilities by giving the user additional arms. Therefore, we chose to map the robotic arm/hand movements directly with the leg/toe movements of the user. In addition to legs being the closest extremities to arms in terms of degrees of freedom and reach, there is an added benefit for mastering control as we are already familiar with how to use our feet in 3D space.

Close Proximity to The Body

In addition to body schema, our brain also keeps a representation of anything in close proximity, or in peripersonal space. Although this space and its encoding are not well understood, research suggests that the boundaries between the peripersonal space and our body schema are fluid [15]. Proximity to the body seems key to having a sense that something is (or is almost) part of one's body. Taking this into consideration, we wanted to place the robotic arms as close to the user's own arms as possible without interfering with them in order to provide the user an egocentric point of view when using the robotic arms, as well as to make it easier for the user to have a sense that the artificial arms are part of his body.

The above consideration led us to decide on a wearable solution: a backpack with the two anthropomorphic arms to be mounted on the user's back.

Feedback Loop

For robotic body extensions, it is not only tracking and translation of motion that are essential. Creating some sort of feedback loop is also crucial, even if it is fairly limited [14]. For our first prototype, we decided on providing force feedback for gripping and touching on the soles of the feet in the hope that this would contribute to the ease and intuitiveness of control.

In addition to these design considerations, we also believe in making our system prototype as accessible as possible so that everybody can experiment with body remapping. Therefore we provide detailed information about the current prototype implementation in this paper and will work towards an open-sourced platform for MetaArms and similar systems.

METAARMS PROTOTYPE

In this section, we describe our exploratory prototype implementation of MetaArms based on the design considerations presented above. Our prototype consists of three basic components: a mobile backpack equipped with two robotic arms, feet tracking devices, and a control software.

Robotic Limbs Backpack

The backpack includes two robotic limbs (arm/hands manipulators), control boards, and a 12V battery. The purpose of making the system as a backpack is to maintain the relationship between body motion on the torso and the arms, so that both are in the same frame. Such design would help maintain consistent coordination and thus consistent operation.

The total weight of the system is about 9 kg, and the dimensions excluding the robotic limbs are shown in Figure 3 . An external PC is used for controlling the system and calculating the coordination of the joints.

Robotic Arms

The arms of this prototype are designed in human scale with 6 degrees of freedom (DoF) to perform free spatial manipu-

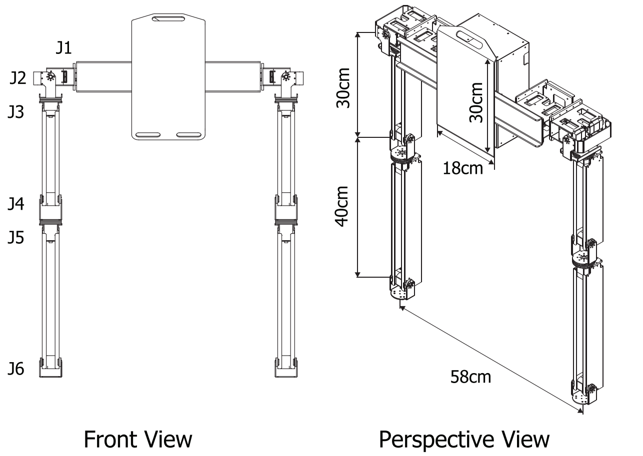

Figure 3. Schematic design of the prototyped backpack arms system.

lations. The end effectors of the arms are designed to accept different types of manipulators (e.g. hand, pointer, tool, etc.), thus allowing for modular design. Figure 3 provides the schematic design of the developed arms, along with the joint placements and the link dimensions.

For driving the arms, servo motors (model Kondo Kagaku B3M-SC-1070-A and B3M-SC-1170-A) were used for the six joints on each arm. The first two joints (J1, J2) are driven using twin motors since these joints would require the highest torque. The rest of the joints (J3-J6) are driven by single motors.

Robotic Hand & Manipulators

On the tip of the robotic arms, where hands would be on human arms, we can attach various manipulators (e.g. robotic hands or more specialized tools). Since our primary focus was on remapping limbs rather than on specific task performance, we first opted for functional robotic hands that can grip and provide tactile feedback. We chose to implement robotic hands based on an open-source artificial prosthetic limb (Exiii HACKberry[1]), a human scale hand with five fingers operated by 3 DoF. We modified the design to add touch sensors for haptic feedback. A pressure sensor (Interlink Electronics FSR 400, FSR 402) is attached to each thumb cushion and palm. These sensors detect the pressure levels when touching an object that are reflected in the feedback.

Foot Tracking & Feedback

We developed a wearable device unit shown in Figure 4 to track the foot position/rotation and the toe posture of the user as well as to provide force feedback to the sole.

The position and rotation of the foot are tracked using an optical-based motion tracking system, HTC VIVE. The tracking unit is attached to the top of the device, providing an absolute measurement of foot postures. We initially investigated the use of IMU-based tracking, but due to tracking latency, accumulated error, and drifting of the measurements, we decided on optical-based sensing for reliable operation.

[1] http://exiii-hackberry.com

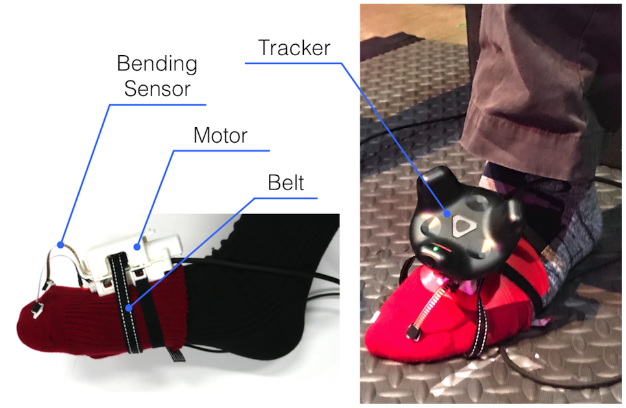

Figure 4. Overview of foot tracking and feedback device.

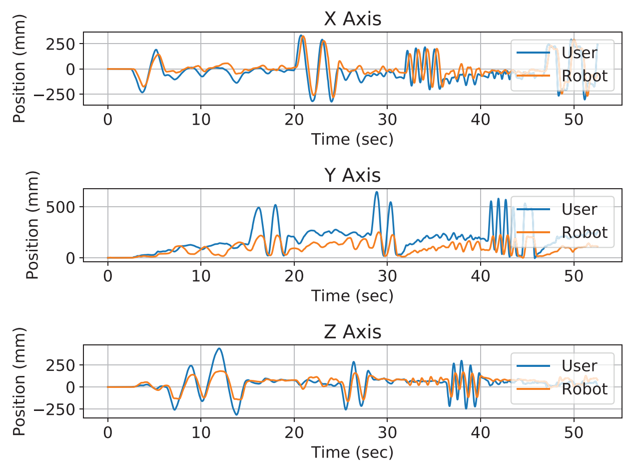

Figure 5. Mechanical time lag and limits between each of user's motion and the corresponding robot limb's motion for each of the three axes (X,Y,Z).

The toes are used to drive the end-effectors, and we employ resistance-based bending sensors to detect toe postures (Spectra Symbol Flex Sensor 2.2"). The tip of the sensor is attached on the upper part of the toes on a sock, and the root of the sensor is connected with the device unit on the arch of the feet. Based on the posture of the toes, the sensor bends accordingly. We deployed an initial calibration to detect the minimum and maximum bending levels of the user's toes.

Force feedback to the sole is provided by a motor-driven belt mechanism [28]. Two motors are placed inside of the device unit (MAXON DC 134849, 0.75 W). A belt is wrapped around the user's foot, and each of the belt's ends is attached to the motor shaft. The user can feel force feedback on the sole of their foot as the belt grips on the foot according to the pressure value reported by the associated robotic hand's touch sensors.

Technical Analysis

The system's mechanical design was evaluated by measuring the mechanical latency during an arbitrary operation. Using an optical tracking system (HTC VIVE trackers), the motion of the user and that of the corresponding robotic end effector were captured. Figure 5 shows the motion signals for each of the three axes (X, Y, Z) for both the user and the robot. The mechanical time lag was measured through cross-correlation between the control position (User), and the measured position (Robot). Mechanical motion limits and time-lag results are reported in Table 1 .

Axis	Motion Limit(mm)		Time Lag(ms)	
	Min	Max	Mean	STD
X	-281	325	195	40
Y	-250	250	375	400
Z	-163	180	140	62.5

Table 1. Mechanical evaluation of the system.

As is shown, Y Axis suffered the highest time lag, which suggests an effect by gravitational force.

ONE ARM POINTING TASK EVALUATION

To evaluate the performance of our system and get some insights into potential learning, fatigue and embodiment effects, we conducted a two-directional Fitts' Law study according to ISO 9241-9 [40, 19]. The tests were conducted with one robotic arm, as most of the participants were not accustomed to manipulating the system.

Apparatus

Fitts' Law [10, 25] states that the index of difficulty (ID) is influenced by the distance from the center point to any of the targets and the width of the said targets:

$$ID = log_2(\frac{A}{W} + 1) \quad (1)$$

A is the amplitude, or distance where W is the width of target in unity units. The targets in this experiment were modeled as white circles on a 2D screen. At the start of the experiment, one of the targets is rendered red and the participant is asked to touch it with the robotic arm/hand. Then another target, located on the opposite of the previously selected target, turns red, until each of the targets are activated. The session ends when the latest activated circle comes back to the first position. During the experiment, we also recorded the movement time (MT) of the whole trial for each input. At the beginning of each trial round (i.e. when a new circle turned red), the position of the robot arm was reset to face the center of the screen. At the point of selection, we also measured the standard deviation (SD) for over-shoots and under-shoots from the center of the target circle. We used the SD values to calculate the effective width (We) shown below:

$$We = 4.133 * SD \quad (2)$$

This allows us to compute the effective index of difficulty (IDe) and the final throughput (TP).

$$IDe = log_2(\frac{A}{We} + 1) \quad (3)$$

$$TP = \frac{IDe}{MT} \quad (4)$$

For the duration of the experimental tests, we employed a think-aloud protocol: the participants were free to express their opinions and provide feedbacks at any time, which were then recorded.

Experimental Setup

As shown in Figure 6 , the experimental setup consisted of a chair in which the participants sat, facing a display that prompted the pointing task. The display measured 930 mm $\times$ 485 mm ($W \times H$), which was enough to cover the arm reach.

The chair was adjusted so the arm's initial position pointed at the center of the screen before starting the experiment in order to normalize the initial condition of the study for all participants.

For this experiment, the robotic hand was replaced with a pointer module to facilitate the clicking task on the screen. This module contained a pressure sensor that measured when the pointer touched the screen. An optical marker was attached to the pointer to track its spatial position and orientation as well as to identify its projected location on the screen coordinates.

The experiment was conducted in a well-lit room and sufficient space for the user's feet to move without special constraint.

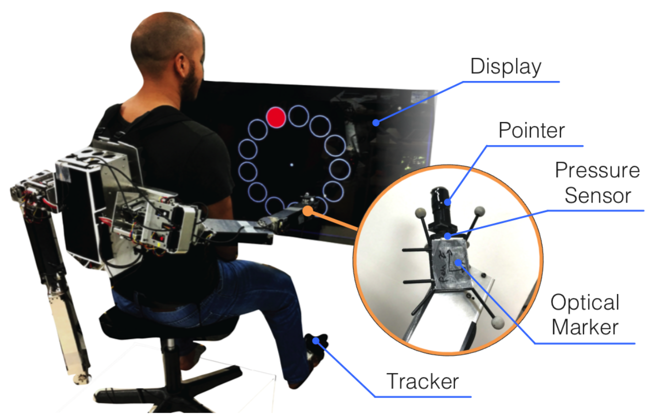

Figure 6. Experimental setup overview.

Participants

Twelve participants (10 male, 2 female) voluntarily joined the study at the local university. Participants' age ranged from 22 to 39 year-old (Mean=26.5, STD=5.0). No participants experienced any physical disabilities and all had fully functional right legs. Only one participant (female) was left-leg dominant as reported in the pre-test questionnaire (See next section for more detail). All participants provided their informed consent prior to starting the study and were informed about the procedure and the approximated length of the study.

Procedure

Prior to starting the experiment, participants provided basic information, including age, gender, height, and answered some questions on physical exercise. They were also asked to describe if they were currently suffering from any physical injuries. The evaluative study consisted of four sessions for each participant. Each session lasted for approximately 10 minutes. Between pointing-task sessions, the participant confirmed his readiness and that he had had enough rest. During each session, a participant performed a Fitts' Law pointing task with different index of difficulties (ID) and a total of 13 targets for Number of Targets ($Fitts_{NoT}$). The order of the sessions (in terms of difficulty) was randomized, as well as the order of the first target for each Fitts trial. Fitts parameter (A/W) values used in the experiment, along with the corresponding IDs (calculated using Eq. 1) of their combinations, are reported as follows:

$A = 250mm, 350mm$
$W = 40mm, 75mm$
$ID = 2.12\ bits, 2.50\ bits, 2.86\ bits, 3.29\ bits$

After each trial, a random white circle appeared on the monitor in one of the four corners ($X: \pm 200mm, Y = \pm 100mm$ from the center of the screen) for two seconds. The user was asked to remember its location, and then point at its memorized location with their eyes closed. The purpose of this step was to measure body coordination without visual feedback (Haptic feedback was still presented when the arm touched the screen). The distance to the target from the point of contact was measured and stored for each trial.

The total number of pointing and clicking tasks per session were calculated as follows:

$$\begin{aligned} N_{clicks} &= (Fitts_{NoT} + 1) \times N_{trials} \\ &= (13 + 1) \times 4 \\ &= 56\ clicks \end{aligned}$$

At the end of each session, the user answered the NASA Task Load Index for perceived task load [13], and rated four statements adopted from the rubber hand illusion experiment [5]. The statements are related to the subjective feeling of the participants:

- How much the robotic arm feels like a part of their own body.
- How much it looks like their own arm.
- How much they feel they control it as part of their own body.
- If the haptic feedback feels like it it is caused by the robotic arm.

For each of the statements, the participants were asked to rate how much it held true for them on a 7-point Likert scale from 1 ("not at all true for me") to 7 ("very true for me"). The participants were also asked to fill a questionnaire to assess their subjective Embodied Sense of Self Scale (ESSS) [2]. The ESSS is a summary measure of several subjective embodiment assessments including Ownership, Agency, and Narrative tested on a large cohort (700+ users) [23, 27].

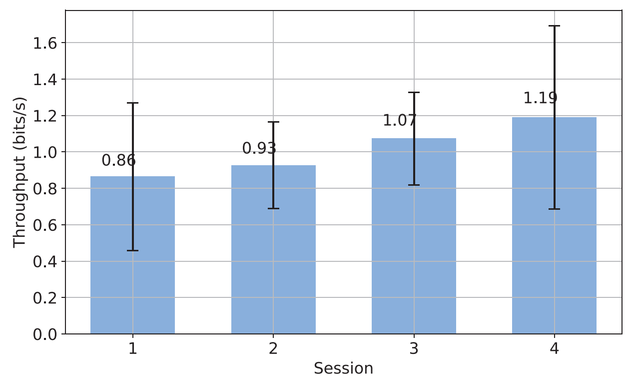

Figure 7. Throughput of pointing task over four sessions.

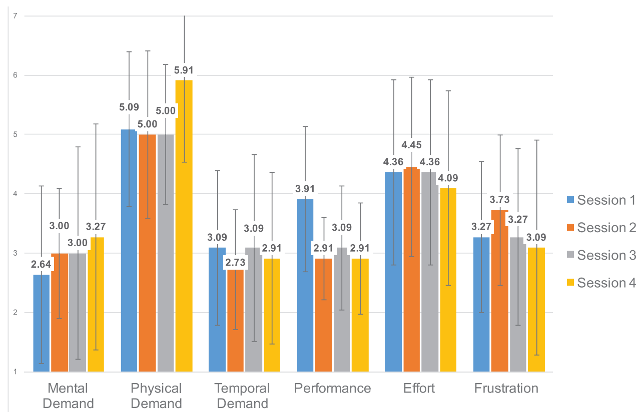

Figure 8. NASA Task Load Index of the 12 participants.

RESULTS AND DISCUSSION

Throughput

The mean throughput for this system for all participants over all sessions was 1.01bits/s with a standard deviation of 0.39bits/s. Figure 7 shows the throughput for each session across all participants. Movement times between targets ranged between 0.42s and 9.66s (mean=3.23s STD=1.35s) across all sessions. For comparison, Young et al. [46] reported 1.08bits/s with a movement speed varying between 1.0s to 2.4s for a 6 DoF input device that used arm motion. Although the throughput of our system was a bit lower, this is perhaps not surprising given the novelty of carrying out a pointing task with foot motion

Task Load Index

The standard deviation decreased noticeably in the second and third session, but later increased for the fourth session. We assume this is due to the increase in perceived physical fatigue of the participants (later discussed in Task Load Index section).

Although the throughput increased over the four sessions, we did not find a significant learning effect between the first and fourth session. Applying a two-tailed t-test between the first and the last session results in a p-value of 0.0909. This result

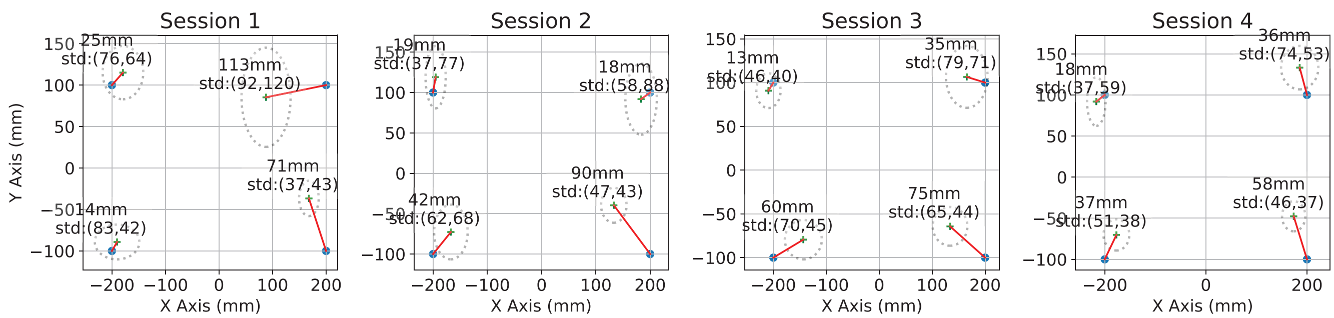

Figure 9. Measured error for all participants over four sessions with eyes closed pointing task

alone, however, cannot suggest anything concrete on learnability as the four sessions took place in a fairly limited period of time.

Figure 8 shows the results of NASA Task Load Index of the 12 participants across four sessions. Strong increases in mental and physical demand through the course of the experiment can be seen. We believe this is partly due to the standard Fitts' Law experimental setup: the users could not put down their controlling leg during the task and had to continue pointing for the entire session. They only rested in between sessions. This is quite different from what we consider to be more normal usage, such as we observed during demonstration sessions (The demo observation will be discussed more later). Some participants complained about slight muscle ache in the right hip (most likely Iliacus muscle) after performing the 4th iteration. Despite the reported physical fatigue by the participants, the perceived performance, effort, and frustration improved over the four sessions. This may indicate that the participants started to learn how to map their feet motion to the new artificial limb, even though such perceived improvements were not reflected in the objective measurements.

Self-reported Embodiment

The statements related to the subjective look, feel and embodiment did not show any significant results. However, the answers to the statement about control *"I felt like I controlled the robot arm as if it was part of my own body."* showed a significant change over the four sessions. Comparing all participants' answers given after the first session with the answers after the last session, the participants reported a significant increase in feeling that the robot arm is part of their body. As expected, the users found it hard to associate the robotic arm with their own as we installed a pointer rather than a robotic had to perform the Fitts'Law experiments (see Figure 6). Also, the statement about the touch was not significant.

The answers to the statement about control show a significant change over the four sessions *"I felt like I controlled the robot arm as if it was part of my own body."*. Comparing all answers from the 12 participants from the first session with the answers from the last, the participants reported a significant increase in feeling that the robot arm is part of their body.

The paired t-test between the Session 1 answers for the control statement (M=3.5, SD =1.43) and the fourth Session 4 answers (M=5.0, SD =1.5) results in $p < 0.005$ (DF = 12). Given the very small sample size (12 participants), we also calculated the effect size $E = E/S(\vec{\Delta}) * S(\vec{\Delta})$ (T-statistic and non-centrality parameter) to be 1.072, which is medium also indicating a significant result. Additionally, we performed the Mann-Whitney U test and obtained results indicating moderate significance: The U-value is 45. The critical value of U at $p < .05$ is 45. The Z-Score is -2. The p-value is -0455.

Body Coordination

After the standard Fitts' Law experiment, we briefly displayed a white circle in a randomly selected corner on the screen. Our aim was to measure the adaptation of the new body coordination without continuous visual feedback. Figure 9 shows the projected error over the four sessions for all participants. Although the mean error of the distance to the center of the circle remains, it decreased over the course of four sessions along with the standard deviation, providing indications of enhanced temporal proprioceptive adaptation.

The most dominant error was caused by the vertical axis (Y), which can be correlated with the mechanical latency of the arms (reported in the Technical Analysis), as well as the difficulty to move the feet upward for tall people due to the setup.

APPLICATIONS

During the course of the prototyping, development, user testing, and exhibitions of our system, we collected a variety of application scenarios for MetaArms . The possibility of coaction between the four arms can help facilitate complex tasks that are difficult to be achieved by a single person. Figure 1 (A) shows a user exchanging the contents of four cups in parallel without any second user support. We imagine the possibility of using such an approach for industrial or professional applications. For example, Figure 1 (C) shows a scenario which the end effector of one arm is replaced with a soldering tool, allowing the user to complete more complex soldering tasks without assistance.

So far, the envisioned application scenarios fall into three categories: substitution, augmentation, and experimentation.

Substitution includes applications for amputees or people with arm/hand disabilities. For example, Figure 1 (B) shows how MetaArms can be used to hold and manipulate objects. We had semi-formal interviews with stroke patients and hand/arm amputees who showed great interest in using this system.

Augmentation focuses on use cases where additional hands/arms obviously are needed. For example holding a component part and soldering (see Figure 1 (C)). This is suitable in situations and applications where the legs are not used (for example, in seated position).

Experimentation explores what other use cases may be made possible by remapping limbs. This exploration may be best pursued in the realm of art and performance, such as playing multiple instruments at the same time, or juggling with four arms.

Remapping could let us reimagine what our bodies can do, rather than simply filling an existing need or augmenting what we already do.

INFORMAL EVALUATION

For informal evaluation, we showcased the MetaArms system at three events (two domestic, one international) for a total of 12 days, around 7 hours a day with over 230 users. They were conferences and laboratory events attracting mostly researchers, professionals and tech enthusiasts. The user demographic was unexpectedly diverse, however, from a 13-year old child to a 67-year-old professor emeritus. Such diverse demographic helped us find some height limitations of the current system where users smaller than 1.30 m or taller than 1.90 m have trouble operating or wearing it.

Most demonstration interactions lasted for approximately 10-15 minutes. Most users could successfully operate the system. Typical demonstration interactions included gripping gestures to hold a cup or shake a hand, playing with tennis balls, and interacting with other people. A user succeeded in throwing a ball with their normal hand and catching it with their robotic limb after a few trials. We think that the adaptation time of operating the robotic arms is highly relevant to system's operation speed and response (current system performance is reported in the Technical Analysis). Many users spontaneously tried to touch their nose or make drinking gestures with the cup, though these gestures did not work as we restricted the artificial limb movement to prevent injuries.

CONCLUSION AND FUTURE WORK

In this paper we have presented MetaArms, an exploratory feet-controlled robotic arms prototype, to examine the feasibility of using limb remapping for operating wearable extra robotic arms with haptic feedback. We introduced a new framework for mapping foot motions to new artificial limbs based on our design considerations. We presented a first prototype implementation of MetaArms as well as technical analysis, the results from a standardized Fitts' Law experiment and subjective feedbacks from the user tests and large-scale demonstration sessions. Overall, the system worked reasonably well within the set parameters, and in some cases seemed to succeed in temporarily eliciting the feeling of having two additional arms.

Regarding future work, we will need to address a number of technical limitations of our current MetaArms system as well as limitations of haptic feedback in general. For instance, we want to improve the lag between tracking and actuation to get below 100 ms for all three axes to induce the feeling of instantaneous movement. This might be especially difficult for the y-axis (which is affected by gravity). Also, we are planning to improve the haptic feedback, moving from simple force feedback to more complex haptic interactions, such as using electric muscle stimulation on the leg [24]. Even with the limitations of our study and our exploratory prototype, we hope and believe that MetaArms with its body remapping approach would create a space of play for exploring and reimaging what the human body could do.

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REFERENCES

1. K Carrie Armel and Vilayanur S Ramachandran. 2003. Projecting sensations to external objects: evidence from skin conductance response. *Proceedings of the Royal Society of London B: Biological Sciences* 270, 1523 (2003), 1499–1506.
2. Tomohisa Asai, Noriaki Kanayama, Shu Imaizumi, Shinichi Koyama, and Seiji Kaganoi. 2016. Development of embodied sense of self scale (ESSS): exploring everyday experiences induced by anomalous self-representation. *Frontiers in psychology* 7 (2016), 1005.
3. Anna Berti and Francesca Frassinetti. 2000. When far becomes near: Remapping of space by tool use. *Journal of cognitive neuroscience* 12, 3 (2000), 415–420.
4. Baldin Llorens Bonilla and H Harry Asada. 2014. A robot on the shoulder: Coordinated human-wearable robot control using coloured petri nets and partial least squares predictions. In *Robotics and Automation (ICRA), 2014 IEEE International Conference on*. IEEE, 119–125.
5. Matthew Botvinick and Jonathan Cohen. 1998. Rubber hands 'feel' touch that eyes see. *Nature* 391, 6669 (1998), 756–756.
6. MC Carrozza, B Massa, S Micera, R Lazzarini, M Zecca, and P Dario. 2002. The development of a novel prosthetic hand-ongoing research and preliminary results. *IEEE/Asme Transactions on Mechatronics* 7, 2 (2002), 108–114.
7. Meng Chen, Bufu Huang, and Yangsheng Xu. 2008. Intelligent shoes for abnormal gait detection. In *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*. IEEE, 2019–2024.
8. Andy Clark. 2003. Natural-Born Cyborgs: Minds, Technologies, and the Future of Human Intelligence. (2003), 116.
9. R Fearing. 1986. Implementing a force strategy for object re-orientation. In *Robotics and Automation. Proceedings. 1986 IEEE International Conference on*, Vol. 3. IEEE, 96–102.

10. Paul M Fitts. 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology* 47, 6 (1954), 381.
11. Koumei Fukahori, Daisuke Sakamoto, and Takeo Igarashi. 2015. Exploring Subtle Foot Plantar-based Gestures with Sock-placed Pressure Sensors. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 3019–3028.
12. Fabian Göbel, Konstantin Klamka, Andreas Siegel, Stefan Vogt, Sophie Stellmach, and Raimund Dachselt. 2013. Gaze-supported foot interaction in zoomable information spaces. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems*. ACM, 3059–3062.
13. Sandra G Hart. 2006. NASA-task load index (NASA-TLX); 20 years later. In *Proceedings of the human factors and ergonomics society annual meeting*, Vol. 50. Sage Publications Sage CA: Los Angeles, CA, 904–908.
14. Matej Hoffmann, Hugo Marques, Alejandro Arieta, Hidenobu Sumioka, Max Lungarella, and Rolf Pfeifer. 2010. Body schema in robotics: a review. *IEEE Transactions on Autonomous Mental Development* 2, 4 (2010), 304–324.
15. Nicholas P Holmes and Charles Spence. 2004. The body schema and multisensory representation (s) of peripersonal space. *Cognitive processing* 5, 2 (2004), 94–105.
16. Atsushi Iriki, Michio Tanaka, and Yoshiaki Iwamura. 1996. Coding of modified body schema during tool use by macaque postcentral neurones. *Neuroreport* 7, 14 (1996), 2325–2330.
17. Steve Jacobsen, E Iversen, D Knutti, R Johnson, and K Biggers. 1986. Design of the Utah/MIT dextrous hand. In *Robotics and Automation. Proceedings. 1986 IEEE International Conference on*, Vol. 3. IEEE, 1520–1532.
18. Eduardo Kac. 1997. Foundation and development of robotic art. *Art Journal* 56, 3 (1997), 60–67.
19. Luv Kohli, Mary C Whitton, and Frederick P Brooks. 2013. Redirected Touching: Training and adaptation in warped virtual spaces. In *3D User Interfaces (3DUI), 2013 IEEE Symposium on*. IEEE, 79–86.
20. Peter J Kyberd and Paul H Chappell. 1994. The Southampton Hand: an intelligent myoelectric prosthesis. *Journal of rehabilitation Research and Development* 31, 4 (1994), 326.
21. Sang-won Leigh, Kush Parekh, Timothy Denton, William S Peebles, Magnus H Johnson, and Pattie Maes. 2017a. Morphology Extension Kit: A Modular Robotic Platform for Customizable and Physically Capable Wearables. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, 397–400.
22. Sang-won Leigh, Harpreet Sareen, Hsin-Liu Cindy Kao, Xin Liu, and Pattie Maes. 2017b. Body-Borne Computers as Extensions of Self. *Computers* 6, 1 (2017), 12.
23. Matthew R Longo, Friederike Schüür, Marjolein PM Kammers, Manos Tsakiris, and Patrick Haggard. 2008. What is embodiment? A psychometric approach. *Cognition* 107, 3 (2008), 978–998.
24. Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 11–19.
25. I Scott MacKenzie. 1992. Fitts' law as a research and design tool in human-computer interaction. *Human-computer interaction* 7, 1 (1992), 91–139.
26. Angelo Maravita and Atsushi Iriki. 2004. Tools for the body (schema). *Trends in cognitive sciences* 8, 2 (2004), 79–86.
27. Jessie E Menzel. 2010. The psychometric validation of the physical body experiences questionnaire. (2010).
28. Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. 2007. Gravity grabber: wearable haptic display to present virtual mass sensation. In *ACM SIGGRAPH 2007 emerging technologies*. ACM, 8.
29. Joseph A Paradiso, Kai-Yuh Hsiao, Ari Y Benbasat, and Zoe Teegarden. 2000. Design and implementation of expressive footwear. *IBM systems journal* 39, 3.4 (2000), 511–529.
30. Federico Parietti and H Harry Asada. 2014. Supernumerary robotic limbs for aircraft fuselage assembly: body stabilization and guidance by bracing. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 1176–1183.
31. Federico Parietti, Kameron Chan, and H Harry Asada. 2014. Bracing the human body with supernumerary robotic limbs for physical assistance and load reduction. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 141–148.
32. Domenico Prattichizzo, Monica Malvezzi, Irfan Hussain, and Gionata Salvietti. 2014. The sixth-finger: a modular extra-finger to enhance human hand capabilities. In *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*. IEEE, 993–998.
33. AF Rovers and HA Van Essen. 2005. FootIO-design and evaluation of a device to enable foot interaction over a computer network. In *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint*. IEEE, 521–522.
34. Tomoya Sasaki, MHD Yamen Saraiji, Charith Lasantha Fernando, Kouta Minamizawa, and Masahiko Inami. MetaLimbs: Multiple Arms Interaction Metamorphism. In *ACM SIGGRAPH 2017 Emerging Technologies (SIGGRAPH '17)*. ACM (New York, NY, USA).

35. Henning Schmidt, Stefan Hesse, Rolf Bernhardt, and Jörg Krüger. 2005. HapticWalker—a novel haptic foot device. *ACM Transactions on Applied Perception (TAP)* 2, 2 (2005), 166–180.
36. Adalberto L Simeone, Eduardo Velloso, Jason Alexander, and Hans Gellersen. 2014. Feet movement in desktop 3D interaction. In *3D User Interfaces (3DUI), 2014 IEEE Symposium on*. IEEE, 71–74.
37. D Spampinato, Hannah J Block, and P Celnik. 2017. Cerebellar-M1 connectivity changes associated to motor learning are somatotopic specific. *Journal of Neuroscience* (2017), 2511–16.
38. Stelarc. 1980. Third Hand. (1980). http://stelarc.org/?catID=20265 (Last accessed July 2018).
39. David J Sturman and David Zeltzer. 1994. A survey of glove-based input. *IEEE Computer graphics and Applications* 1 (1994), 30–39.
40. Robert J Teather and Wolfgang Stuerzlinger. 2011. Pointing at 3D targets in a stereo head-tracked virtual environment. In *3D User Interfaces (3DUI), 2011 IEEE Symposium on*. IEEE, 87–94.
41. Vighnesh Vatsal and Guy Hoffman. 2017. Wearing your arm on your sleeve: Studying usage contexts for a wearable robotic forearm. In *Robot and Human Interactive Communication (RO-MAN), 2017 26th IEEE International Symposium on*. IEEE, 974–980.
42. Eduardo Velloso, Dominik Schmidt, Jason Alexander, Hans Gellersen, and Andreas Bulling. 2015. The feet in human–computer interaction: a survey of foot-based interaction. *ACM Computing Surveys (CSUR)* 48, 2 (2015), 21.
43. Faye Wu and Harry Asada. 2014. Bio-Artificial Synergies for Grasp Posture Control of Supernumerary Robotic Fingers. In *Proceedings of Robotics: Science and Systems*. Berkeley, USA.
44. Faye Y Wu and H Harry Asada. 2015. "Hold-and-manipulate" with a single hand being assisted by wearable extra fingers. In *Robotics and Automation (ICRA), 2015 IEEE International Conference on*. IEEE, 6205–6212.
45. Weizhong Ye, Yangsheng Xu, and Ka Keung Lee. 2005. Shoe-Mouse: An integrated intelligent shoe. In *Intelligent Robots and Systems, 2005.(IROS 2005). 2005 IEEE/RSJ International Conference on*. IEEE, 1163–1167.
46. Thomas S Young, Robert J Teather, and I Scott MacKenzie. 2017. An arm-mounted inertial controller for 6DOF input: Design and evaluation. In *3D User Interfaces (3DUI), 2017 IEEE Symposium on*. IEEE, 26–35.
47. Adam B Zoss, Hami Kazerooni, and Andrew Chu. 2006. Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX). *IEEE/ASME Transactions On Mechatronics* 11, 2 (2006), 128–138.