Through Feet, Connecting to SuperLimbs

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Abstract

SuperLimbs (Supernumerary Robotic Limbs) are a robotic approach for extending physical capabilities in human augmentation. In this position paper, we introduce our research on foot-based SuperLimbs operation. Based on the insights gained from our previous activities, we overview the research challenges and prospects about three topics: sensing, modeling, and body perception. Through these topics, we explore the potential of foot-based SuperLimbs control and interface, with references to HCI, robotics, and neuroscience, and discuss the next generation of foot augmentation technology.

CCS Concepts

• **Computer systems organization** → *Robotics*; • **Hardware** → *Sensors and actuators.*

Keywords

Body Remapping, Wearable Device, Embodiment

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1 Introduction

In human augmentation research, robotic approaches to enhancing human physical functions are called SuperLimbs (Supernumerary Robotics Limbs) [5], which have been actively researched for the recent decade. These approaches build and attach extra limbs such as arms, fingers, legs, and tails to the human body that limbs do not naturally possess. These robotic limbs, for example, expand the user's manipulation abilities and enhance balance functions. SuperLimbs originally began in part from the context of wearable robots, particularly exoskeleton robots, and expanded to other research areas such as HCI and cognitive science. Unlike conventional exoskeletons, an interesting research issue is how to achieve intuitive control of the additional limbs as the user intends, which requires interdisciplinary approaches. About this research issue, we have taken approaches focusing on foot, developed interface devices, and proposed a control method for robot arms using foot motion [7, 8].

MetaLimbs [8] enables the user to control two wearable robot arms and hands using wearable sensors attached to both feet to capture foot motion. The user's foot motion links to the robot's movement and haptic feedback is provided to the foot through the robot's hand touching, and this continuous feedback loop connects the user to robotics limbs. This allows the user to operate the two robot arms independently of the movements of their own hands, and to perform coordinated tasks and multitasking using four arms at the same time. We call this approach Body Remapping and have explored its potential through experiments and prototype demonstrations [7].

In this position paper, we will discuss the research challenges and prospects of foot augmentation related to SuperLimbs based on the insights gained from our previous experience, focusing on three topics: sensing, modeling, and human body perception.

2 Research Challenges and Prospects

2.1 Sensing for Body Remapping

First, about sensing, we believe that the foot interface used for human augmentation with SuperLimbs needs to be able to acquire more precise and diverse information. Various sensing devices have already been developed for foot augmentation. However, their majority scope is pressure or force on the sole, walking motion, and foot posture sensing [3]. We measured the toe posture to control the robot hand to open and close it. Such an attempt has rarely been undertaken especially with SuperLimbs, and we developed a sensor device, DataSocks, for system implementation (Figure 1).

Figure 1: Prototypes of DataSocks for sensing toe posture.

While demonstrating our prototype in various locations, we observed that the shape of the foot and toes is more diverse than that of the hand and fingers. Just as shoe sizes vary from person to person, there are large individual differences in the width and size of the sole and foot, in particular, in the length and range of motion of the toes. This diversity makes it difficult to ensure accurate sensing and affects the wearability of devices. In our device, from the perspective of data robustness, we measure the bending motion of the entire toe with 1–2 degrees of freedom. In addition to

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the individual differences in the foot and toe shapes, the common lifestyle of wearing shoes limits the explicit movement of the toes, and the form factor of the shoes becomes a constraint on sensing techniques. For example, the vision-based sensing methods generally used in hand tracking cannot be directly applied to the toe because shoes hide the toe, and the placement of the camera is limited. For this reason, our prototype requires users to remove their shoes during the experience. Exploring another solution, we have proposed a sensing method using photo reflective sensors attached to the ankle [4]. This method allows users to wear shoes while sensing, but it has not achieved accurate capture of toe motion.

Not only the toes but also the legs can be used for SuperLimbs control, and we actually use the global motion of the lower body, including the legs and feet, to control the robot arm. In general, since leg sensing can be done as part of full-body motion capture, more technology options can be used compared to toe sensing. However, there is another issue in modeling movements that differ from conventional activities, which will be discussed in the next section.

Prospects from the perspective of sensing lay that research is expected to be conducted on acquiring high-precision and diverse information on the entire lower body, including the toes and legs, in order to expand the technology cultivated through foot augmentation to a wider area. In addition, it would be necessary to respond to individual differences in foot shapes and restrictions on sensing method selection to a greater extent than with hand sensing. These developments would expand SuperLimbs applications that incorporate foot interaction in actual situations.

2.2 Modeling and Motion Understanding

In robot control, it is common practice to use mathematical, kinematics, and dynamics models to check robot behavior in simulations before using the actual robot. For human modeling, various studies on digital humans have been explored, and recently, there have been attempts to connect full-body human body models with robot models, including multi-point contact motion [9]. Modeling of the human body using motion capture has already been common, and full-body motion includes lower motions. Also, there are studies on the anatomical characteristics of the feet, legs, and lower limbs and the range of motion of these joints. However, many of these data are based on typical motions in daily life, such as walking and getting up from a chair. While these conventional studies are necessary, we believe that the scope of modeling and motion understanding of the foot should be expanded to not only these typical motions but also to a wider range of foot motions under various contexts of human augmentation.

Our prototype requires users to perform physical movements that they would not usually perform when controlling robot arms using their feet. For example, when performing manipulation by grasping a cup with the robot hand and moving it close to their mouth, the user has to raise their foot while keeping their toes closed as shown in Figure 2a. This kind of task performance is expected to depend on whether or not they can move foot and toe in coordination, and such complex movements are difficult to classify or evaluate using conventional analysis frameworks such as for walking or standing up. As shown in Figure 2b, We conducted system verification for foot-based operations using pointing tasks [7], but this is an early stage and further investigation is needed.

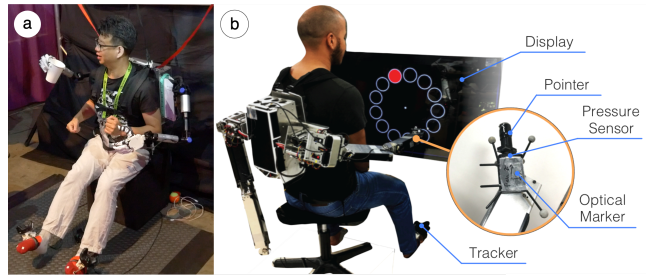

Figure 2: (a) Foot movements required to control our prototype. (b) Experimental setup for a foot-based pointing task from [7].

In robotics, the operation ability of the leg is defined as "pedipulation" and there is research on motion planning [2]. However, this approach is not expanded to investigating the operability of the human foot. There are conventional neuroscience studies on the motor equivalence of hand and foot movements using writing tasks [6]. In HCI, there are also many studies on the workspace and operability of the hand. In a form that builds on the various studies that have been conducted in related research fields, we hope that research will be conducted on the operability and modeling of the foot. A deep understanding of foot motion leads to further exploration of the differences between the foot and hand, and it would open new research frontiers. Obviously, the perspective of body perception cannot be ignored. We discuss this topic in the next section.

2.3 Body Perception and Embodiment

In addition to the construction of the physical modeling of the human body, the discussion of a cognitive model and body perception is also an interesting topic in human augmentation. In SuperLimbs research, some groups explore from the perspective of how body perception changes when new body parts are attached. This covers broader scopes of not only physical functions but also cognitive and existence augmentations. For example, research issues include investigating how to reduce cognitive load for additional limb manipulations and how external robotic systems are incorporated into our motor control. These lead to the understanding of the mechanisms of cognition and body perception. A study [1], which reproduced a similar control system as MetaLimbs in a VR space and conducted a user study, reported that users can feel supernumerary limb sensation through tasks despite being operated with the feet.

When mentioning the relationship between neuroscience and SuperLimbs, brain-machine interfaces (BMI) using brain activity and bio-signals-based operation are often compared to our body remapping approach. Our approach requires physical movement for motion sensing and controlling robots, whereas the BMI and bio-signals approach has the potential to be operated by intention or slight muscle movements. However, current technologies still require acquiring a large amount of data for each individual to perform calibration, and the measured signals are not robust due to low signal-to-noise ratio, in most cases. On the other hand, body motion sensing has the advantage of being used for a relatively large number of users with a simple calibration in a short time. Furthermore, we believe that the foot-based SuperLimbs control has potential advantages during the learning process, even after the ultimate BMI-based SuperLimbs control is realized in the future.

We can easily imagine a situation where our hands and arms are moving in the brain while we don't move our bodies. This is because we have a long experience of using our hands and arms. On the other hand, it is difficult to imagine a situation where a third and fourth hand are moved with our own hands together at the same time, because most people have no such experience. Even if such body image is formed in the brain, it is supposed that the brain activities of each individual will significantly differ because there is no reference connection with the body for motor control. In that case, even if the BMI works, it will be necessary to specify the detection area of the brain for each individual at each time.

Our hypothesis is that if the foot-based SuperLimbs operation is performed several times, a body image that includes control of extra limbs is formed with a connection to the motor area related to the foot. After sufficient experience in using the feet to control, it is possible to acquire the body image of moving extra limbs without moving the actual feet. This learning process will reduce individual differences and specify the range of the active area in the brain, and it helps robust sensing for BMI. We believe that kind of learning and adaptation process are essential for future physical and cognitive augmentation and the foot augmentation approach will help to explore this research direction. To verify this hypothesis, further detailed investigations are necessary in cooperation with interdisciplinary teams including such as neuroscientists, psychologists, and engineers of BMI technology.

3 Conclusion

In this position paper, we discussed three topics based on our experience during research on SuperLimbs control using the feet. (1) Sensing: we mentioned the potential of expanding the sensing scope not only to conventional foot but also to lower limbs including the toe and legs, and described the technical challenges involved in sensing the toes. (2) Modeling: we proposed updating foot motion modeling from typical ones such as walking to those focusing on operability and introduced the efforts in related fields. (3) Body perception: we presented a hypothesis that the foot-based SuperLimbs control contributes to the learning process in future BMI. These topics we discussed are wide-ranging and expect many further technological advances in hardware and software, as well as scientific discoveries related to human understanding. We believe that foot augmentation is one of the exciting approaches to tackling these topics, and we look forward to future developments alongside SuperLimbs research.

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References

[1] Ken Arai, Hiroto Saito, Masaaki Fukuoka, Sachiyo Ueda, Maki Sugimoto, Michiteru Kitazaki, and Masahiko Inami. 2022. Embodiment of supernumerary robotic limbs in virtual reality. *Sci. Rep.* 12, 1 (June 2022), 9769. doi:10.1038/s41598-022-13981-w

[2] Rafael Cisneros, Kazuhito Yokoi, and Eiichi Yoshida. 2013. Impulsive pedipulation of a spherical object for reaching a 3D goal position. In *2013 13th IEEE-RAS International Conference on Humanoid Robots (Humanoids)*. IEEE, 154–160. doi:10.1109/humanoids.2013.7029970

[3] Don Samitha Elvitigala, Jochen Huber, and Suranga Nanayakkara. 2021. Augmented Foot: A Comprehensive Survey of Augmented Foot Interfaces. In *Augmented Humans Conference 2021 (AHs'21)*. Association for Computing Machinery, New York, NY, USA, 228–239. doi:10.1145/3458709.3458958

[4] Kosuke Kikui, Katsutoshi Masai, Tomoya Sasaki, Masahiko Inami, and Maki Sugimoto. 2022. AnkleSens: Foot posture prediction using photo reflective sensors on ankle. *IEEE Access* 10 (2022), 33111–33122. doi:10.1109/access.2022.3158158

[5] Domenico Prattichizzo, Maria Pozzi, Tommaso Lisini Baldi, Monica Malvezzi, Irfan Hussain, Simone Rossi, and Gionata Salvietti. 2021. Human augmentation by wearable supernumerary robotic limbs: review and perspectives. *Prog. Biomed. Eng.* 3, 4 (Sept. 2021), 042005. doi:10.1088/2516-1091/ac2294

[6] Marc H Raibert. 1977. Motor Control and Learning by the State Space Model. (Sept. 1977).

[7] MHD Yamen Saraiji, Tomoya Sasaki, Kai Kunze, Kouta Minamizawa, and Masahiko Inami. 2018. MetaArms: Body Remapping Using Feet-Controlled Artificial Arms. *The 31st Annual ACM Symposium on User Interface Software and Technology - UIST '18* (2018), 65–74. doi:10.1145/3242587.3242665

[8] Tomoya Sasaki, MHD Yamen Saraiji, Charith Lasantha Fernando, Kouta Minamizawa, and Masahiko Inami. 2017. MetaLimbs: multiple arms interaction metamorphism. In *ACM SIGGRAPH 2017 Emerging Technologies (SIGGRAPH '17, Article 16)*. Association for Computing Machinery, New York, NY, USA, 1–2. doi:10.1145/3084822.3084837

[9] Eiichi Yoshida. 2022. Towards understanding and synthesis of contact-rich anthropomorphic motions through interactive cyber-physical human. *Front Robot AI* 9 (Dec. 2022), 1019523. doi:10.3389/frobt.2022.1019523

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