HandMorph: a Passive Exoskeleton that Miniaturizes Grasp

Jun Nishida[1] Soichiro Matsuda[2] Hiroshi Matsui[3] Shan-Yuan Teng[1]
Ziwei Liu[1] Kenji Suzuki[2] Pedro Lopes[1]
[1] University of Chicago, USA [2] University of Tsukuba, Japan [3] Ruhr-University Bochum, Germany

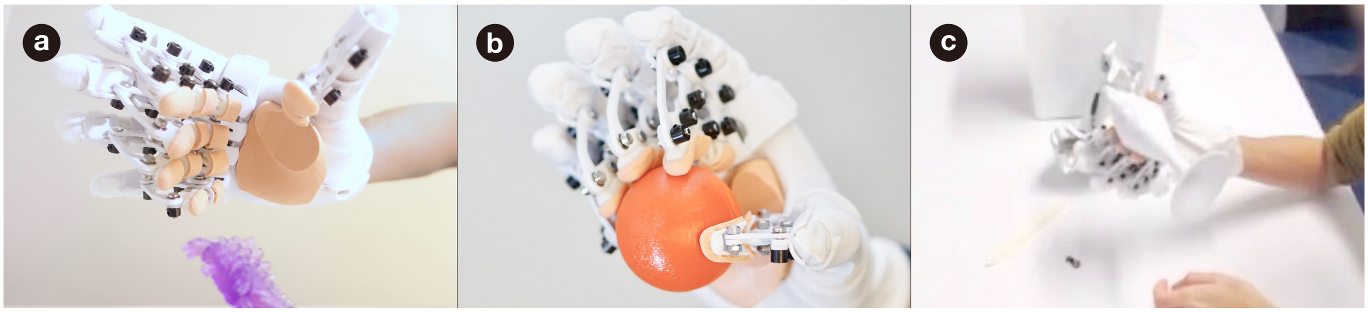

Figure 1. (a) We engineered a passive exoskeleton, HandMorph, that approximates the experience of a smaller grasping range. HandMorph uses mechanical links to transmit motion and haptic feedback from the wearer's fingers to a smaller hand. (b) In our first user study, we found that participants perceived objects as larger when wearing HandMorph, which suggests that their size perception was transformed. (c) HandMorph achieves this transformation in the user's real environment. As such, it can, for instance, allow a product designer to change their grasp into that of a child while evaluating a toy. In fact, our second study found that participants felt more confident in their toy designs when using HandMorph to validate ergonomics.

ABSTRACT

We engineered an exoskeleton, which we call HandMorph, that approximates the experience of having a smaller grasping range. It uses mechanical links to transmit motion from the wearer's fingers to a smaller hand with five anatomically correct fingers. The result is that HandMorph miniaturizes a wearer's grasping range while transmitting haptic feedback.

Unlike other size-illusions based on virtual reality, HandMorph achieves this in the user's real environment, preserving the user's physical and social contexts. As such, our device can be integrated into the user's workflow, e.g., to allow product designers to momentarily change their grasping range into that of a child while evaluating a toy prototype.

In our first user study, we found that participants perceived objects as larger when wearing HandMorph, which suggests that their size perception was successfully transformed. In our second user study, we assessed the experience of using HandMorph in designing a simple toy trumpet for children. We found that participants felt more confident in their toy design when using HandMorph to validate its ergonomics.

Author Keywords

Exoskeleton; Haptics; Perception; Embodied Design

UIST '20, October 20–23, 2020, Virtual Event, USA

ACM ISBN 978-1-4503-7514-6/20/10 ...$15.00.
http://dx.doi.org/10.1145/3379337.3415875

INTRODUCTION

Embodied interaction tells us that "how we understand the world, ourselves, and interaction comes from our location in a physical and social world" [14, 15]. Many researchers characterize it as *moving interactions away from a screen and into the real world*, which has been a central tenet of many schools of thought in HCI, such as tangibles [32] or somaesthetics [26, 29].

In fact, one of the key challenges in embodiment is to design devices that allow a user to temporarily *feel* the bodily experience of another person. For example, researchers have shown that embodying a virtual reality (VR) avatar of a different size can change one's perception of size or distances [5, 41, 70] and even one's behaviour [18, 85]. Unfortunately, while previous embodiment devices are powerful, they only work in VR and not in the user's social and physical environment.

As such, researchers have turned to wearable devices that enable users to experience the sense of having a different body, while in the real world. Examples include wearables that allow a user to see the world through the height of a smaller person via a waist mounted camera and a AR headset [21, 54]. While these wearables allow the user to look from the eyes of a smaller person, they do not allow the user to interact with objects through the hand of the smaller person.

To tackle this, we propose a wearable, depicted in Figure 1, that transforms the user's grasping and reaching range into that of a person with a smaller hand. To achieve this, we engineered a passive hand-exoskeleton, which we call HandMorph, that achieves its grasp transformation via mechanical linkages that transmit movements from the user's fingers to a set of five anatomically-correct small rubber fingers.

Moreover, we purposely designed HandMorph using mechanical linkages to also transfer haptic information to the user, such as pressure, which is key to enabling dexterous manipulation.

We found via two user studies, that: (1) when using HandMorph participants perceived that objects were larger, suggesting that their grasping range was transformed into that of someone with a smaller hand; and, (2) participants felt more confident in their designs when designing a toy trumpet for children using HandMorph to validate the toy's ergonomics.

While we acknowledge that a grasp-illusion could perhaps be realized in virtual reality, we believe that achieving it in the real world affords a wider range of applications, including interactions with real objects that promote a more embodied design process [15, 29].

RELATED WORK

The work presented in this paper builds primarily on body representation/ownership illusions from the field of haptics.

Plasticity in body representation

Our brain maintains an updated map of our *body representation*, which holds spatial information of our limbs' shape, dimensions, and positions [45, 49, 50]. Our sensory experiences, such as touch and visual feedback, contribute to constructing and updating our body representation at every instant [47, 48]. It has been shown that our body representation is plastic and can even be extended to include objects that are not originally part of our body [24, 31, 36, 47]. A canonical example of this plasticity is the Rubber Hand Illusion [8], in which a user feels that a dummy rubber hand [20] or a smaller doll [74, 75, 76] has become the physical embodiment of their own body. The illusion relies on the user seeing the rubber hand be passively touched while simultaneously feeling that touch on their own hand. Similarly, it has been shown that during active tool use, such as when manipulating a simple stick, our body representation is enlarged [9, 47, 49, 52, 67].

Illusions using virtual avatars

Virtual reality (VR) has been leveraged to transform body representation. For instance, VR was used to create an illusory ownership of a virtual child's body [5, 70], to transform user's hands into smaller virtual hands [40, 42, 57], to see oneself with a different virtual skin tone [46, 59], and to create the sensation of a taller body [85] or scaled arms [34, 41]. These demonstrate that changing (the virtual) bodies in a virtual environment is effective in changing one's perceptions, actions, and behaviors [18, 85]. Therefore, many postulate that the application of these experiences may help users gain empathy toward different people [6, 66]. However, all these illusions can only be realized in closed-off virtual environments using virtual avatars. We believe that by pursuing these illusions in a real-world environment, we can allow users to also benefit from interactions with people and surrounding objects.

Changing body ability through wearable devices

With recent advancements in wearable actuators, it is possible to change one's body abilities into those of another person, for instance, a user can: simulate and feel the effects of age on their own movement range [55, 61, 63] or, even, feel a different body [7, 13, 22, 83]. These devices are different from the aforementioned VR approaches in that they are fusing visual and haptic sensations in the real world. These devices are most used to provide a more empathic understanding to other people's conditions [7, 13, 55].

Two canonical examples of transformations of the user's body ability in real time are: *AGNES*, is a passive wearable suit that uses: elastic bands to limit the user's range of motion, gloves to suppress tactile feedback and a pair of goggles that tint the user's vision; the device allows the user to feel the abilities of elderly people inducing motor and visual impairments [10, 37]; and, *CHILDHOOD*, a wearable system that shifts down a user's visual perspective in real-time using a combination of a waist mounted camera and a headset has proposed [54]. While the latter allows a user to see the world from the perspective of a smaller person, it does not allow the user to grasp objects as if they had the hand of a smaller person. To achieve this transformation of one's grasp, exoskeletons are required.

Exoskeletons

Exoskeletons are the primary device for haptic feedback in VR, tele-existence and rehabilitation. "Active" exoskeletons possess sufficient actuation power (typically by means of large motors or pneumatic actuators) to move the user's body. One popular interactive application for exoskeletons is force feedback in VR [1, 16, 19, 73]. Exoskeletons are also used for remotely controlling robotic hands [53] or for hand rehabilitation [3, 11, 23, 77]. Moreover, supernumerary robotic limbs (e.g., attaching a third hand) [27, 28, 38, 39, 64, 65, 84] or active prostheses [35, 58] have also been explored as means to transform physical hand ability. While active exoskeletons are useful in applications that require force feedback or restoring loss motor function, they also come at the expense of bulky form factors and decoupled haptic sensations, e.g., when using an exoskeleton to control an external robotic hand, one cannot feel what the robotic hand feels without adding sensors to the external hand and actuators to one's hand.

In fact, studies have shown that the lack of haptic feedback or its delay affect the sense of control and ownership toward external limbs [2, 17, 68]. As such, researchers have turned to "passive" mechanisms that provide realtime, and congruent haptic feedback [78, 79]. Furthermore, passive exoskeletons are generally safer than their actuated counterparts. We take these aspects into account in our system's exoskeleton design.

Body transformations using passive exoskeletons

Passive exoskeletons have been used to transform ability, such as by giving users a different body size [51, 72]. Another example is a hand-exoskeleton [56] that achieves a smaller hand; this is an earlier prototype related to ours. However, the authors did not evaluate whether the prototype was successful at creating the perceptual transformation of the user's grasping range through a controlled laboratory experiment. First, our present work differs by the validation of this phenomena. Second, our prototype outperforms the previous one [56] in three ways: (1) we utilized a four-bar linkage, which transmits the finger motion at the last edge of the finger segments; (2)

we reduced friction on the small hand by splitting the fingers into their constituent segments, rather than connecting them via a rigid link (see Implementation); and, lastly, (3) we added a rubber palm and a linkage for the thumb finger; altogether, enabling a usable and dexterous experience.

OUR APPROACH: SMALLER HAND EXPERIENCE

Figure 2 depicts how HandMorph approximates the experience of a smaller hand by changing the wearer's **grasping** and **reaching** range, while still allowing the user act in their real-world environment. Our main focus was investigating the transformation of grasping range, rather than reaching range, as such, our studies predominantly focused on this first goal.

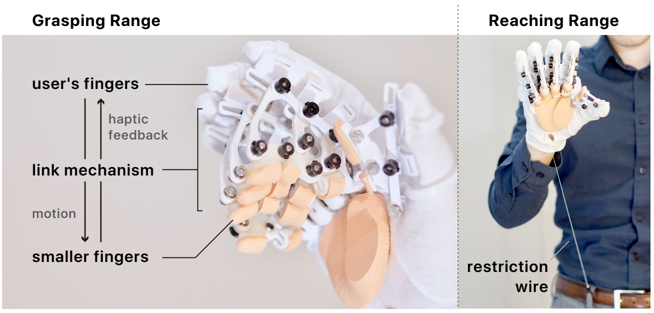

Figure 2. Transformation of the user's grasping and reaching range.

HandMorph transforms the user's grasping range by means of its mechanical linkages, which transmit both movements and force from the user's own fingers to their respective small rubber fingers. By doing so, this mechanism changes the scale of the user's grasping motion, requiring the wearer to fully open their hand when trying to pick up an object that they normally would have grasped with a half open hand. This implementation provides a more realistic somatosensory experience (touch, pressure and proprioception) than just restricting the range of motion of the fingers using wires. This is important since it has been shown that one's perceived grasping ability changes one's overall perception [12, 44, 81, 82]. In fact, internal representation of our hands affects the perceived size of objects we interact with as well as the distances in our surroundings [43]; this is thought to happen because our brains utilize our hands as a "perceptual ruler" to measure the world [60]. Leveraging this fact, we expect that wearing our device will transform the user's perception of the real-world. As such, in our study, we hypothesized and confirmed that real-world objects felt larger while wearing HandMorph.

Lastly, HandMorph also features a wire attached from the user's belt loop to the exoskeleton. As the user reaches out with their hand, this wire restricts their arm's reach. While this is simplistic, it effectively limits the user's reaching range.

CONTRIBUTION, BENEFITS AND LIMITATIONS

Our key contribution was engineering a passive hand-exoskeleton that modifies the user's grasping range. Our user study confirmed that participants perceived objects as larger than they were, when wearing our exoskeleton; this suggests their perception of their own grasping range was transformed.

Our approach has three benefits: (1) **real-time and congruent haptics:** unlike active exoskeletons which require sensors and actuators, our passive-hand allows users to experience real-time haptics (e.g., pressure) without any perceptual delay–a direct benefit of our link mechanism. (2) **real-world:** unlike illusions of body transformation that can only take place in VR, our device enables the hand's perceptual transformation to happen anytime, anywhere, preserving user's physical and social contexts. This allows it to be used in tasks such as prototyping toys, exploring usability of products for people of all sizes, and so forth. Lastly, (3) **safe and walk-up-use:** as our device reproduces movements from the user's fingers to the passive-hand's fingers without using powered actuators, it is fairly easy and safe to use even without any explanation (refer to our exploratory sessions for examples of this)—making our device ideal for real-world activities such as product design (e.g., designing and evaluating toys for children).

Our device is not without its limitations. First, as with any passive exoskeleton, its range of transformation and the glove dimensions are fixed by its mechanism. Therefore, while the current range works (see our studies), changing it would require re-manufacturing. In fact, in our studies, we observed a few participants whose fingers did not fit ergonomically in the glove; however, we believe that future versions of this design will easily mitigate inter-subject variability by either customizing each glove a particular user or using variable-length linkages. Moreover, users see a cover that hides their own fingers. We acknowledge that this might diminish the effect of our perceptual transformation. However, solving this would require either using VR, which in turn loses all the tangible benefits of operating in a real-world, or integration with complex computer vision systems that would project back the environment onto the user's hands, rendering them "invisible" (e.g., [30]).

IMPLEMENTATION

To help readers replicate our design, we now provide the necessary technical details. To accelerate replication, we provide the 3D models of our device[1]. Our exoskeleton, depicted in Figure 3, is divided into four components: **(1) finger sockets** to attach the exoskeleton to the user's hand (link S_i); **(2) link mechanism** to transmit the grasping motion (link B_i, $B_{i,j}$, C_i); **(3) flexible silicone** skins for smaller fingers and a palm to simulate skin-like haptic feedback; and, **(4) 40 cm wire** with a carabiner to restrict the range of motion of the user's arm.

Our device is inspired by previous work [56] but solves many of the challenges that the previous implementation exhibited. In particular: (1) it allows for movement in all five fingers; (2) our linkages (described below at greater length) are based on a four-bar linkage, which drastically reduces friction at the last edge of the finger segments; and, (3) our small hand is not rigid but instead is comprised of several rubber finger segments; this greatly reduces friction on the mechanism while increasing friction between the smaller hand and the objects it contacts with, thus increasing the dexterity of our device.

[1] https://lab.plopes.org/#handmorph

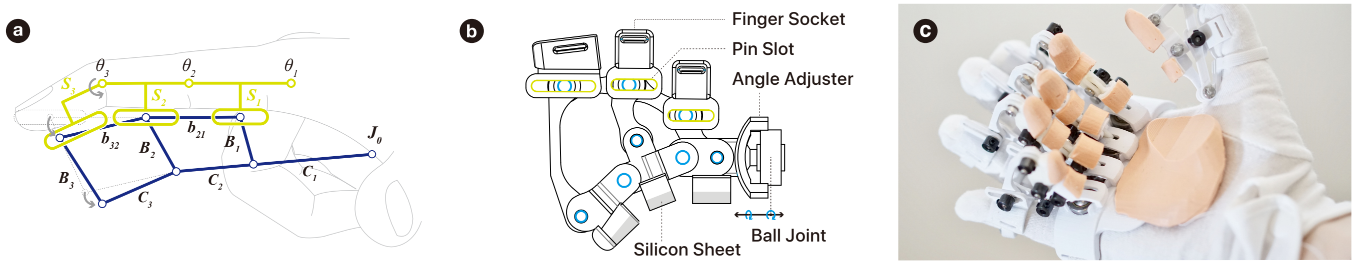

Figure 3. (a) Link model that transmits the finger motion to the smaller rubber fingers (b) CAD model of the link mechanism. The rubber fingers are achieved with plastic fingers and silicon sheets (c) Implementation of the exoskeleton. The rubber finger and the palm was created by using molds.

Mechanics

HandMorph transmits motion via a mechanical link based on two four-bar mechanisms, depicted in Figure 3(a). This link consists of three finger sockets (S_1, S_2, S_3) with pin slots, three links that act as smaller fingers (C_1, C_2, C_3), five bridge links ($B_1, B_2, B_3, b_{21}, b_{32}$), and a joint J_0 on the palm.

Figure 3(a) shows that when the distal interphalangeal joint is bent, the fingertip pushes down the bridge link B_3, which transfers the motion to the smaller finger link C_3. Thus, the user's finger position is replicated by the smaller hand. Since the distance between each socket S_i will decrease as fingers bent, a pin slot was attached to the sockets S_i to translate movement from each joint to the bridge links b_{21}, b_{32} (the green ellipse in Figure 3(a)). The length of this pin slot is the critical factor that determines the grasping range. In order to calculate its length, we measured the angular displacement of each finger joint using an OptiTrack V100 R2 motion capture system for a full grasping motion (all five fingers). Then, by means of a simulation in Autodesk Fusion 360, we obtained the minimum pin length required to achieve this motion range.

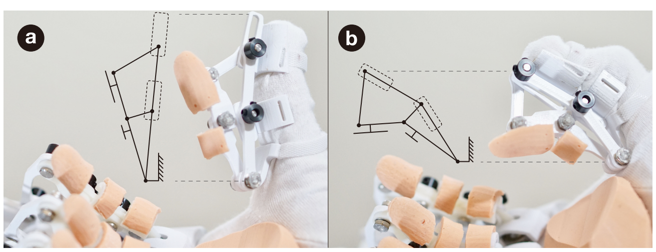

Figure 4. The thumb mechanism achieves (a) the extension and (b) the flexion while preserving unconstrained thumb movements.

Figure 3(b) shows our link mechanism for one finger. Joint J_0 was achieved with a ball joint with two degrees-of-freedom (DOF) and a short linkage that connects the C_1 link to the ball joint. Each small link C_i has a finger shaped appendage coated with a silicone sheet surface. A palm attachment with a stretchable band is used to hold the four finger link mechanisms. The thumb mechanism is independent from these, to allow for unconstrained thumb movements, and anchors to a small pad around the user's thumb base, as shown in Figure 4.

Manufacturing

The entire exoskeleton was manufactured from polylactic acid plastic in a Ultimaker 3 3D printer. The fingers were coated with a sheet of liquid rubber 2mm (Dragon Skin FX-Pro) with a skin color pigment, resulting in the soft look depicted in Figure 3(c). The exoskeleton's total weight is 171g.

Scaling factor between user's hand and HandMorph

To determine the movement scaling factor (i.e., how much the user's finger movement is amplified or reduced by our linkages), we measured the joint angles from an open hand to a closed hand pose, for the index finger mechanism with one participant. From these, we calculated an angular scaling factor by dividing the HandMorph's finger movement by the user's finger movement. This simple test revealed that: the distal interphalangeal joint amplifies movement with a factor of 3.97; the proximal interphalangeal joint slightly reduces movement (0.74); and the metacarpophalangeal joint has almost no impact on movement scaling (0.95). Note that the four-fold amplification of our first joint is intentional, as it enables users to easily grasp objects given that any rubber fingers lack the level of friction and dexterity of actual hands.

OVERVIEW OF USER STUDIES

We conducted two user studies to validate HandMorph: **(1) size perception experiment**, in which we found that the grasped objects were perceived to be larger; and, **(2) simple toy design session**, in which we examined participants' experiences with HandMorph; we found that they felt more confident in their simple toy designs when using HandMorph to test their design's ergonomics. Lastly, we also took HandMorph outside the lab and observed that visitors were able to use it without instructions.

STUDY 1: INVESTIGATING SIZE PERCEPTION

The objective of this study was to understand how our HandMorph impacted size perception of objects participants interacted with. This measurement provides direct insights of whether the user's grasping experience was transformed. Therefore, our study was a size perception experiment modelled after [80].

Our hypothesis was that if HandMorph transformed a participant's grasp into that of a smaller hand, then objects would feel larger than they actually were. This prediction was grounded in previous studies that reported that when participants embodied a smaller body in VR [5, 70] or by means of the rubber hand illusion [74, 75, 76], objects would to be perceived as larger. However, since HandMorph does not require VR, we utilized **real objects**. Our study was approved by our Institutional Review Board (IRB19-1431).

Apparatus

Figure 5 depicts the setup used in our experiment. Participants wore an earlier model of our exoskeleton glove on their dominant hand, which did not feature the thumb mechanism. To constrain the thumb movement into the adequate range we featured a restriction wire. The exoskeleton was covered with a white cloth to encourage participants into observing the small exoskeleton-fingers rather than their own fingers.

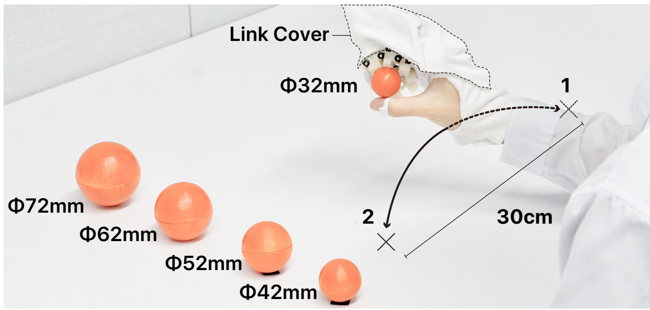

Figure 5. Experimental setup used in our grasping range experiment.

Participants were asked to interact with five plastic balls of different diameters, ranging from 32mm to 72mm (in steps of 10mm). There were two positions on the table, 30cm apart, marked with "1" (start position) and "2" (end position).

Trial Design

In each trial, participants were asked to: (1) pick up a ball, (2) move it from start to end position, (3) move it back to start position, and (4) squeeze it three times. Then, the experimenter took off the exoskeleton hand. Following this, we asked participants to demonstrate the perceived size of the ball they just interacted with by posing their index finger and thumb, with their eyes closed, as if they were holding the ball; this allowed us to focus on their kinesthetic experience. The experimenter measured this distance using a digital caliper with sub-millimeter precision.

Procedure

Participants experienced the aforementioned task in two conditions: with **HandMorph** and with their **OwnHand**. The order of these two conditions was counterbalanced across all participants. In each trial, participants were provided one new plastic ball at random, each ball was shown three times (repetitions). Only one ball was at the table at all times of the study. In total, each participant performed a total of 360 trials (five ball diameters × three repetitions × two conditions).

At the end of all conditions, participants were asked three Likert scale questions regarding their experience including perceived grasping range (Q_1), the feeling of control (Q_2) and ownership (Q_3) toward the exoskeleton. We asked participants to fill in a Likert scale, as shown in Figure 7; this questionnaire was based on that of [8, 54]. To examine body representation in detail, we also asked them to choose or draw their hand representation, as shown in Figure 8. They were asked to answer these questions on a 7-point scale for Q_1 (-3 = decreased, 3 = increased) and a 6-point scale for $Q_{2,3}$ (1 = disagree, 6 = agree).

Participants

We recruited 12 healthy right-handed participants from our local organization (six self-identified as female; six as male; mean age = 23.9 years old, SD=2.54). Participants were compensated with 10 USD for their time. No participant had previously tried an exoskeleton.

Results

Figure 6 shows our main findings, i.e., the result of the perceived object size with/without the exoskeleton.

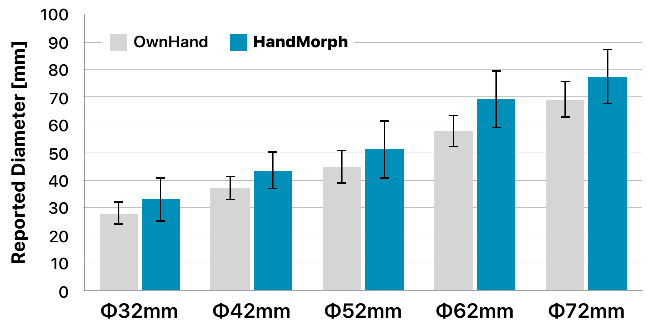

Figure 6. Participants' perceived object size in both conditions. We found that objects were perceived to be larger when using *HandMorph*.

A two-way repeated measures ANOVA revealed a significant difference in the main effect between the two interface conditions ($F(1,110) = 25.7, p < 0.001$). This suggests that our main hypothesis was confirmed, i.e., when using **HandMorph** participants perceived objects to be larger ($M = 54.7mm, SD = 20.0mm$) compared to when using their **OwnHand** ($M = 47.6mm, SD = 16.2mm$). Furthermore, we found no interaction between the two interface conditions and the ball's diameter ($p = 0.39$).

Qualitative findings

At end of the study, we asked the participants about their experience using three Likert scale questions and a multiple-choice question regarding their perceived body representation.

Grasping range

As depicted in Figure 7, the questionnaire results indicate that participants felt that their grasping range decreased when using HandMorph (Q_1; score=-1.77, SD=1.25). Participants also reported a clear sense of agency while the controlling HandMorph (Q_2; score=4.31, SD=1.32), while their sense of ownership was relatively low (Q_3; score=2.77, SD=1.19).

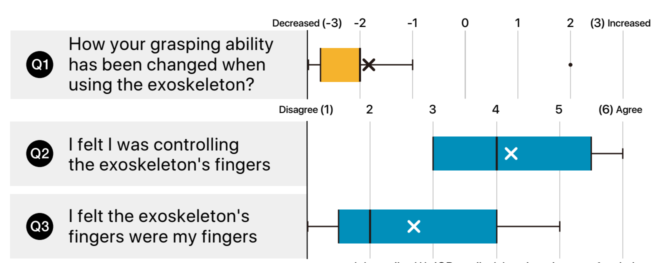

Figure 7. Participants' experience with regards their grasping range, agency and ownership while wearing our exoskeleton.

Hand representation

Figure 8 depicts the six hand representations presented to participants in our multiple choice question: (a) nothing has changed; (b) my entire hand became smaller; (c) four fingers became smaller; (d) four fingers became thicker; (e) Had additional fingers; and, (f) participants could draw their own representation if none of the above were fitting. Figure 8 also depicts our results: four participants perceived as if their hand became smaller; six participants perceived as if their four fingers became thicker; and, one participant drew in which their four fingers became thicker and smaller (Figure 8(f)). This insight provides further indicates that, indeed, participants' hand representation was changed by **HandMorph**.

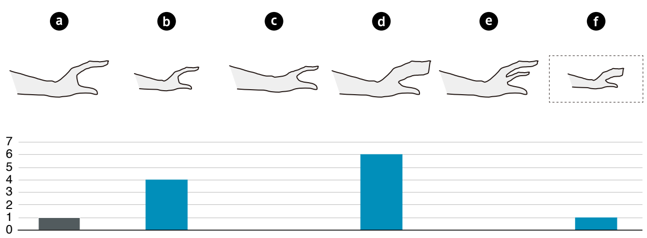

Figure 8. Participants' perceived hand representation. We found that 11 (out of 12) participants reported their hand felt smaller or the distance between the four fingers and the thumb felt shorter.

Discussion

Altogether, our quantitative and qualitative results suggest that participants perceived their hands were smaller while using HandMorph to grab the objects. Still, we believe a few other factors should be discussed in light of our findings.

Perceived object size

We believe the main factor driving the perception of objects being enlarged while using our exoskeleton-hand was somatosensation, i.e., sense of touch and proprioception. We find this to be the case since, while using our exoskeleton, participants could not see their fingers. Furthermore, one could suspect the perception of an enlarged object came from visual comparisons between the object and the small rubber fingers. However, we do not believe this to be the case, since we asked participants to judge the size of the object blindfolded; precisely to understand the impact of proprioception over visuals. Still, visual information might affect size perception as well. Characterizing precisely the impact of each sensory modality might require further examination. Furthermore, combining the smaller grasp enabled by our exoskeleton with the lower visual perspective of prior work [54], one could potentially achieve a change in both size and distance perception.

Limitations of our device

Additionally, discrepancies between participant's skin and the exoskeleton's silicone skin, the unaltered size of the thumb (which we addressed in our subsequent prototype), and the changes in tactile feedback via the link mechanism could also contribute to a lower sense of ownership.

Impact of ownership and perceived ability

One participant mentioned that a failure to grasp a ball in a single trial lowered their sense of agency and ownership towards our exoskeleton. We acknowledge that an outcome bias could affect the score [81], i.e., failure in grasping could decrease the sense of ownership.

Moreover, prior research suggested that participants exhibit a higher sense of ownership for larger virtual hands than for smaller virtual hands [4], which could also contribute to the lower sense of ownership observed by our participants when using our smaller hand.

STUDY 2: EXPERIENCING HANDMORPH IN DESIGN

While in our first study we focused on a psychophysical experiment to understand the impact on perception, our second study investigated whether HandMorph could assist in evaluating/designing products for people with smaller hands. Therefore, we asked participants to improve the design of a simple toy trumpet to be used by smaller persons, such as children (ages 3-10). Our study was approved by our Institutional Review Board (IRB19-1431).

Apparatus

Our study apparatus is depicted in Figure 9. Participants were provided with modeling clay and a set of typical modeling tools (e.g., a spatula, a ruler, etc.) to quickly fabricate their toy designs. A 3D printed toy trumpet was provided as an initial design, as depicted in Figure 10(a).

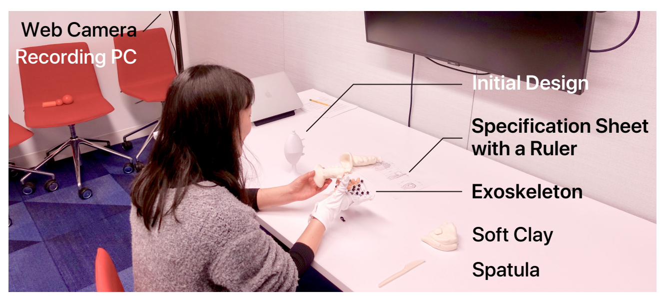

Figure 9. Experiment Setup: Participants designed a small toy trumpet, using clay, meant for children (ages 3-10). To assist them, we provided: a specification sheet with hand dimensions or an average child and our exoskeleton.

Additionally, participants were presented with two tools to assist them in ensuring that the resulting prototype was ergonomic for children: (1) **HandMorph**: our prototype with all five fingers (Figure 1); and, (2) **SpecSheet**: a US-Letter size specification sheet, which is depicted in Figure 10(b) and provides full ergonomic details with the average dimensions of the hand and fingers of children (ages 3-10). The provided SpecSheet was adapted from the hand dimension diagrams in Tiley et al.'s human factors for design textbook [71]. This specification illustrated the average dimensions (ages 3-10) for hand (length, breadth, and grip radius) and fingers (length, thickness, breadth, diameter), which were obtained from previous studies [25].

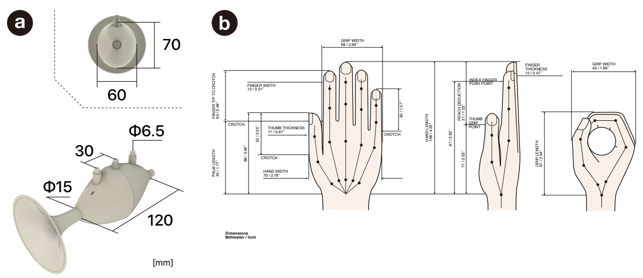

Figure 10. Apparatus: (a) initial design of the toy trumpet, and (b) specification sheet in which its graphic design is adapted from an actual book.

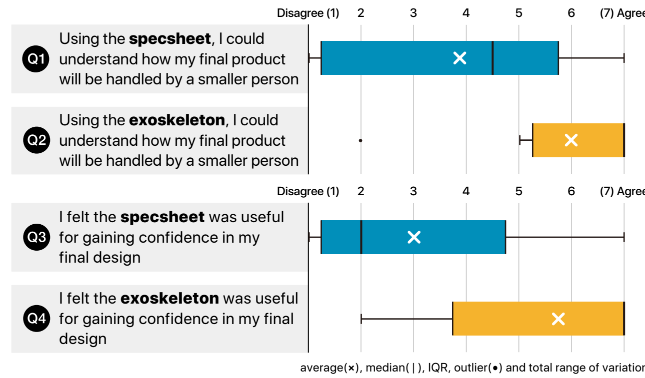

Figure 11. Participants' reports of their experience and confidence in their designs while wearing *HandMorph* or using *SpecSheet*.

Procedure

Prior to the start of the trials, we asked participants to get acquainted with HandMorph for one minute, during this time we asked them to interact with the balls from Study 1. Likewise, we walked them through the information on the SpecSheet. Then, participants were given a maximum of 30 minutes to (1) **evaluate and improve** the accessibility of the toy trumpet provided by the experimenter, and (2) **present their design** using modeling clay. Prior to the start of the trial, we informed participants that their resulting trumpet was targeted at children (ages 3-10) and that they could use both the exoskeleton and the specification sheet anytime.

Participants

We recruited eight new right-handed participants from our institution (four self-identified as female; four as male; mean=25.6 years old, SD=4.3). Participants were not professional designers but had all taken design classes in college. Participants were compensated with 10 USD for their time. No participant had previously tried any exoskeleton. With their consent, we video-recorded all trials for analysis.

Results

Overall, we found out that: (1) participants felt that HandMorph provided them more confidence in their designs; (2) participants used HandMorph, on average, five times more often than the SpecSheet, in quicker design bursts, mostly for testing ergonomics; and, (3) participants improved five out of six flaws in the initial design.

Questionnaire

Figure 11 depicts the main findings from our questionnaire. Regarding how much using the tools improved judgements on the ergonomics of their designs, participants rated the HandMorph on average as 6.0 (out of 7; SD=1.8) and the SpecSheet on average as 3.9 (out of 7; SD=2.3); this suggests that participants felt empowered by HandMorph to enable better ergonomic judgements. Furthermore, regarding how much using the tools improved confidence in their designs, participants rated the HandMorph on average as 5.75 (out of 7; SD=2.1) and the SpecSheet on average as 3.0 (out of 7; SD=2.1); this suggests participants felt that the HandMorph provided them more confidence in their designs.

Video-observations and Interviews

We found that participants used HandMorph an average of five times (SD=3.77) and SpecSheet on average only once (SD=1.29). The average single usage time was 68s (SD=53.2; includes time to put it on/off) for HandMorph and 79s (SD=79.9) for SpecSheet; suggesting that HandMorph was used for quicker and shorter evaluations, while the SpecSheet was used once for a longer period of time.

We observed that five participants (out of eight) wore HandMorph right at the start to evaluate the initial design's ergonomics, as shown in Figure 12-(1). P6 was the most extreme case as they wore HandMorph throughout the complete session, including while modeling. When interviewed at the end, two participants remarked on using HandMorph to feel that the initial design was "too big for grasp or pick up" (P1 and similarly P3); P5 added "[I] felt pain [from stretching] my palm when tried to grab". Conversely, three participants started by consulting the SpecSheet; one of these (P7), spent two minutes studying the SpecSheet but ended up using HandMorph for rest of the session, depicted in Figure 12-(4).

Figure 12. Participants used HandMorph for assessing ergonomics.

When asked about what drove participants to use HandMorph: P1 added "[evaluating] body size and button placement so that the instrument can be held comfortably, and letting [my] fingers move quickly and easily"; P3 stated "grab [it] to emulate how [a] smaller hand would feel"; and, P4 added, "verifying positions [that I] can reach, grab and use comfortably", as shown in Figure 12-(2). To our surprise, three participants used HandMorph to actually model the clay, creating design strategies such as marking finger shape and distance on the clay with HandMorph (Figure 12-(3)), or squeezing the clay to decrease the toy's diameter until they felt a comfortable grasp.

When asked what drove participants to use the SpecSheet: P3 stated, "approximate the dimension of the whole design"; P4 stated, "to consider potential size"; P2 stated, "I looked at this [SpecSheet] at first because I knew it describes the dimensions precisely. But [later] I found that my early design based on it [SpecSheet] didn't feel right". Furthermore, P2, P5, and P6 experienced some difficulties while calculating appropriate length from the SpecSheet; this is normal as these human factor specifications do not illustrate all possible hand poses.

When asked to compare the tools: P1 added, "the exoskeleton helped me feel out major issues in the design's usability, and was really useful for testing how the instrument would feel"; P5 added regarding the SpecSheet, "numbers didn't help very much"; and, lastly, P7 stated "I relied on [HandMorph] to help me to evaluate the design, test it and to see how confident I am for this to be handled by a smaller hand".

Design Outcomes

Figure 13 shows participants' toys made from modeling-clay. While there is no "perfect solution" for this toy trumpet (i.e., as there are infinite possible designs), there were six challenges in improving the initial design: (1) reduce the length of the main shaft; (2) reduce the grasp radius of the main shaft; (3) reduce the spacing between pistons; (4) reduce the piston's height; (5) increase the piston's cap diameter for an easier targeting; and, (6) add a finger support (where trumpeters rest their thumb and/or pinkie for stability). Guidelines for sizing products denote that graspable parts of a toy for ages above 3 must relate to the user's hand size [62], which for a 3-10 year old child was found to be on average 116.84mm (length) and 53.34mm (breadth) [25, 33]. Participants were unaware of this list or given any clues of what to fix in the initial design.

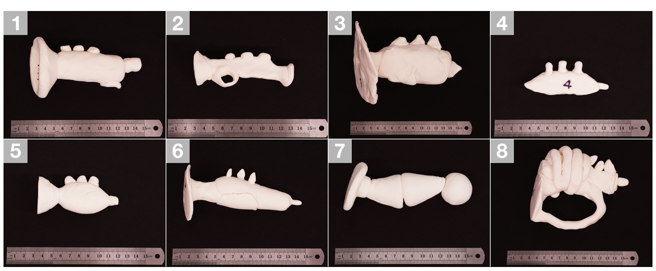

Figure 13. Participants' toy trumpets made from modeling-clay.

Finally, Figure 14 depicts the adjustments that participants made compared to the initial design. We found that all participants corrected five (out of six) flaws by reducing (1) main shaft length; (2) main shaft radius; (3) piston spacing; (4) piston's height; and, by increasing (5) the piston's cap diameter. Lastly, P1/2/3/8 addressed (6) by adding a finger support.

Discussion

Taken altogether, our results suggest that participants embraced HandMorph as a tool for quick iterations, mostly to test ergonomics. Participants used it several times, without mentioning any frustration regarding putting it on or off. Participants used it with surprising dexterity, even modeling the clay while wearing our device. This suggests that HandMorph can be used as a design tool without a long learning-curve.

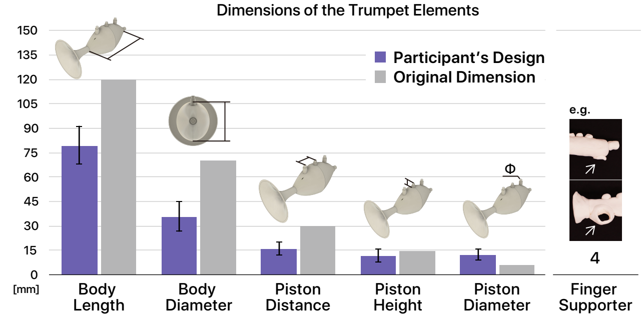

Figure 14. Dimensions of original vs. participant's toy design. Participants successfully adjusted the dimensions of most design elements considering the toy's target audience (children between 3-10 years old).

Our findings regarding number of uses and duration per use, suggest that HandMorph may be seen as complimentary rather than mutually exclusive to existing design tools. Participants used HandMorph many times but in short design bursts, while they tended to use the SpecSheet in longer design iterations.

EXPLORATORY SESSIONS OUTSIDE THE LAB

In addition to our studies, we observed participants' interactions with HandMorph in demonstrations we did at a museum and a local supermarket, depicted in Figure 15. While these sessions did not carry the rigor on our controlled experiments, they allowed us to gather insights of how people reacted to the device in a looser setting without precise instructions. To incite visitors to interact with our device, we set up a table with several objects on display, such as toy cars, eating, and drinking utensils. Then, as visitors approached our table, they were offered our HandMorph device prior to interacting with these objects. Most interactions took around 3 to 5 minutes. In these sessions, we counted over 500 visitors, with the majority at the museum. We did not record demographics since this was not a controlled experiment but visitors were all seemingly adults.

Figure 15. Observations at our exploratory sessions at a museum and a local supermarket (taken with consent of visitors).

Many visitors used HandMorph to manipulate toys and eating utensils, immediately after they wore the exoskeleton, for the first time, with virtually no training. We observed that most visitors quickly understood how to manipulate it, making in fact very few mistakes. This might suggest that the exoskeleton was relatively easy to use.

Several visitors noted, without being prompted, that they felt aware of the difficulties someone with a smaller hand might experience. For instance, one visitor mentioned that they felt difficulties in grasping a water bottle with our exoskeleton hand because the bottle was so large. They suggested that given that these bottles are practically ubiquitous and are also used by children, they could have a small handle, similar to a cup. Moreover, after interacting with the toy cars, many visitors discussed with their fellow visitors (friends or families) about how some of these objects felt excessively large for children's hands while others could be easily picked up and held by children. In the same vein, a supermarket patron used our device and tried to pick up items around the fruit and vegetable section and brought them to a cashier. This visitor stated the difficulty in reaching even a simple apple, noting how a smaller person must have a hard time with these objects at the supermarket.

We also observed unique conversation and attitude change between the user and their fellow visitors (friends or families) such as speaking in a child-like manner or performing grasping reflex, which can be seen in infants, with other fellow visitors. Furthermore, many visitors expressed surprise about the hand size difference when they see and compare both their unrestricted grasp vs. the hand that wears HandMorph.

APPLICATIONS FOR DESIGNERS

While our key contribution is the validation of the transformation of one's grasping range into that of someone with a smaller hand, we think there is a range of interesting avenues to apply our findings; we depict two examples in Figure 16. We believe the main potential of our device lies in feeling the ergonomics of devices designed for people with bodies different from that of the designer. This is especially relevant in the context of designing for children, smaller people, or individuals with motor impairments that affect dexterity. Our device might assist a designer to gain sensitivity to challenges faced by the target users. Figure 16 (a) depicts our device assisting a product designer in evaluating the usability of eating utensils. Figure 16 (b) shows our device being used to reconsider the placement items in a physical space (e.g., a classroom or museum), in a more inclusive manner towards people with short stature. Lastly, we believe HandMorph might be useful for visually-impaired designers since they heavily rely on their somatosensory experience [69].

Figure 16. Applications for HandMorph: (a) evaluating usability of products; (b) investigating the accessibility of physical spaces.

CONCLUSION

In this paper, we engineered HandMorph, an exoskeleton that approximates the experience of having a smaller hand. Leveraging the plasticity of our body's representation, we proposed and verified an illusion that transforms one's grasping range into that of a someone with a smaller hand. HandMorph achieves this using mechanical links that transmit motion from the wearer's fingers to a smaller soft hand with five fingers. As such, HandMorph miniaturizes a wearer's grasping range while transmitting haptic feedback.

Unlike other size- or grasp-illusions based on virtual reality, HandMorph achieves this in the user's real environment while preserving the user's physical and social contexts. As such, our device can be integrated into the user's workflow, e.g., to allow product designers to momentarily change their grasp into that of a child while evaluating a toy prototype.

We conducted two user studies to validate HandMorph. In our first user study, we found out that the participants' perceived objects as being larger when wearing HandMorph, which suggests that their size perception was transformed as if having a smaller hand. In our second user study, we assessed the experience of using HandMorph as an assistive tool for designing a simple toy trumpet for children. We found that participants felt more confident in their toy design when using HandMorph to validate its ergonomics. We believe that, unlike consulting human factors ergonomic charts, the somatosensory feedback felt while using HandMorph helped participants to understand the usability of their designs in a more embodied manner.

Lastly, we find that our device is unique in that it enables the wearer, especially designers, to gain embodied knowledge of the challenges of those with a smaller grasp: children, individuals of short stature or with dwarfism, and so forth.

ACKNOWLEDGMENTS

This work was supported by Grant-in-Aid for JSPS Research Fellow (JP16J03777), Scientific Research on Innovative Areas (JP18H04182) and the BIG Ideas Generator at the University of Chicago. We thank Hikaru Takatori and Kosuke Sato for supporting the demo session.

REFERENCES

[1] Miguel Altamirano Cabrera and Dzmitry Tsetserukou. 2019. GlideReality: A Highly Immersive VR System Augmented by a Novel Multi-modal and Multi-contact Cutaneous Wearable Display. In *ACM SIGGRAPH 2019 Emerging Technologies (SIGGRAPH '19)*. ACM, New York, NY, USA, Article 13, 2 pages. DOI: http://dx.doi.org/10.1145/3305367.3327986

[2] J. Arata, M. Hattori, S. Ichikawa, and M. Sakaguchi. 2014. Robotically Enhanced Rubber Hand Illusion. *IEEE Transactions on Haptics* 7, 4 (Oct 2014), 526–532. DOI:http://dx.doi.org/10.1109/TOH.2014.2304722

[3] J. Arata, K. Ohmoto, R. Gassert, O. Lambercy, H. Fujimoto, and I. Wada. 2013. A new hand exoskeleton device for rehabilitation using a three-layered sliding spring mechanism. In *2013 IEEE International Conference on Robotics and Automation*. 3902–3907. DOI:http://dx.doi.org/10.1109/ICRA.2013.6631126

[4] Laura Aymerich-Franch and Gowrishankar Ganesh. 2016. The role of functionality in the body model for

self-attribution. *Neuroscience Research* 104 (2016), 31 – 37. DOI:http://dx.doi.org/https://doi.org/10.1016/j.neures.2015.11.001 Body representation in the brain.

[5] Domna Banakou, Raphaela Groten, and Mel Slater. 2013. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences* 110, 31 (2013), 12846–12851. DOI: http://dx.doi.org/10.1073/pnas.1306779110

[6] Philippe Bertrand, Jérôme Guegan, Léonore Robieux, Cade Andrew McCall, and Franck Zenasni. 2018. Learning Empathy Through Virtual Reality: Multiple Strategies for Training Empathy-Related Abilities Using Body Ownership Illusions in Embodied Virtual Reality. *Frontiers in Robotics and AI* 5 (2018), 26. DOI: http://dx.doi.org/10.3389/frobt.2018.00026

[7] Arthur Pointeau Bertrand Philippe, Daniel Gonzalez-Franco and Christian Cherene. 2014. The Machine to be Another - Embodied Telepresence using human performers. Prix Ars Electronica. (2014).

[8] Matthew Botvinick and Jonathan Cohen. 1998. Rubber hands 'feel'touch that eyes see. *Nature* 391, 6669 (1998), 756–756. DOI:http://dx.doi.org/10.1038/35784

[9] Lucilla Cardinali, Francesca Frassinetti, Claudio Brozzoli, Christian Urquizar, Alice C. Roy, and Alessandro Farnè. 2009. Tool-use induces morphological updating of the body schema. *Current Biology* 19, 12 (2009), R478 – R479. DOI: http://dx.doi.org/https://doi.org/10.1016/j.cub.2009.05.009

[10] Carlos Cardoso and P. John Clarkson. 2012. Simulation in user-centred design: helping designers to empathise with atypical users. *Journal of Engineering Design* 23, 1 (2012), 1–22. DOI: http://dx.doi.org/10.1080/09544821003742650

[11] A. Chiri, N. Vitiello, F. Giovacchini, S. Roccella, F. Vecchi, and M. C. Carrozza. 2012. Mechatronic Design and Characterization of the Index Finger Module of a Hand Exoskeleton for Post-Stroke Rehabilitation. *IEEE/ASME Transactions on Mechatronics* 17, 5 (Oct 2012), 884–894. DOI: http://dx.doi.org/10.1109/TMECH.2011.2144614

[12] Elizabeth S Collier and Rebecca Lawson. 2017. Does grasping capacity influence object size estimates? It depends on the context. *Attention, perception psychophysics* 79, 7 (October 2017), 2117—2131. DOI: http://dx.doi.org/10.3758/s13414-017-1344-3

[13] E. C. De Oliveira, P. Bertrand, M. E. R. Lesur, P. Palomo, M. Demarzo, A. Cebolla, R. Baños, and R. Tori. 2016. Virtual Body Swap: A New Feasible Tool to Be Explored in Health and Education. In *2016 XVIII Symposium on Virtual and Augmented Reality (SVR)*. 81–89. DOI:http://dx.doi.org/10.1109/SVR.2016.23

[14] Paul Dourish. 1999. Embodied Interaction: Exploring the Foundations of a New Approach to HCI.

[15] Paul Dourish. 2001. *Where the Action is: The Foundations of Embodied Interaction*. MIT Press, Cambridge, MA, USA.

[16] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. 2020. Wireality: Enabling Complex Tangible Geometries in Virtual Reality with Worn Multi-String Haptics. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. DOI: http://dx.doi.org/10.1145/3313831.3376470

[17] C. Farrer, G. Valentin, and J.M. Hupé. 2013. The time windows of the sense of agency. *Consciousness and Cognition* 22, 4 (2013), 1431 – 1441. DOI: http://dx.doi.org/https://doi.org/10.1016/j.concog.2013.09.010

[18] Daniel Freeman, Nicole Evans, Rachel Lister, Angus Antley, Graham Dunn, and Mel Slater. 2014. Height, social comparison, and paranoia: An immersive virtual reality experimental study. *Psychiatry Research* 218, 3 (2014), 348 – 352. DOI:http://dx.doi.org/https://doi.org/10.1016/j.psychres.2013.12.014

[19] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. 2016. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1991–1995. DOI: http://dx.doi.org/10.1145/2858036.2858487

[20] Arvid Guterstam, Valeria I. Petkova, and H. Henrik Ehrsson. 2011. The Illusion of Owning a Third Arm. *PLOS ONE* 6, 2 (02 2011), 1–11. DOI: http://dx.doi.org/10.1371/journal.pone.0017208

[21] Satoshi Hashizume, Akira Ishii, Kenta Suzuki, Kazuki Takazawa, and Yoichi Ochiai. 2018. Trans-scale Playground: An Immersive Visual Telexistence System for Human Adaptation. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings (UIST '18 Adjunct)*. ACM, New York, NY, USA, 66–68. DOI: http://dx.doi.org/10.1145/3266037.3266103

[22] Hans Hemmert. 1997. Level. (1997). https://www.moma.org/interactives/exhibitions/2011/talktome/objects/145507/

[23] Pilwon Heo, Gwang Min Gu, Soo-jin Lee, Kyehan Rhee, and Jung Kim. 2012. Current hand exoskeleton technologies for rehabilitation and assistive engineering. *International Journal of Precision Engineering and Manufacturing* 13, 5 (01 May 2012), 807–824. DOI: http://dx.doi.org/10.1007/s12541-012-0107-2

[24] M. Hoffmann, H. Marques, A. Arieta, H. Sumioka, M. Lungarella, and R. Pfeifer. 2010. Body Schema in Robotics: A Review. *IEEE Transactions on Autonomous Mental Development* 2, 4 (Dec 2010), 304–324. DOI: http://dx.doi.org/10.1109/TAMD.2010.2086454

[25] B Hohendorff, C Weidermann, KJ Burkhart, PM Rommens, KJ Prommersberger, and MA Konerding. 2010. Lengths, girths, and diameters of children's fingers from 3 to 10 years of age. *Annals of Anatomy-Anatomischer Anzeiger* 192, 3 (2010), 156–161.

[26] Kristina Höök. 2009. Affective loop experiences: designing for interactional embodiment. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364 (2009), 3585 – 3595.

[27] Yuhan Hu, Sang-won Leigh, and Pattie Maes. 2017. Hand Development Kit: Soft Robotic Fingers As Prosthetic Augmentation of the Hand. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 27–29. DOI: http://dx.doi.org/10.1145/3131785.3131805

[28] Irfan Hussain, Gionata Salvietti, and Domenico Prattichizzo. 2016. On Control Interfaces for the Robotic Sixth Finger. In *Proceedings of the 7th Augmented Human International Conference 2016 (AH '16)*. ACM, New York, NY, USA, Article 49, 2 pages. DOI:http://dx.doi.org/10.1145/2875194.2875243

[29] K. Höök, K. Friedman, and E. Stolterman. 2018. *Designing with the Body: Somaesthetic Interaction Design*. MIT Press, Cambridge, MA, USA.

[30] Masahiko Inami, Naoki Kawakami, and Susumu Tachi. 2003. Optical Camouflage Using Retro-Reflective Projection Technology. In *Proceedings of the 2Nd IEEE/ACM International Symposium on Mixed and Augmented Reality (ISMAR '03)*. IEEE Computer Society, Washington, DC, USA, 348–. http://dl.acm.org/citation.cfm?id=946248.946825

[31] A Iriki, M Tanaka, and Y Iwamura. 1996. Coding of modified body schema during tool use by macaque postcentral neurones. *Neuroreport* 7, 14 (October 1996), 2325—2330. DOI: http://dx.doi.org/10.1097/00001756-199610020-00010

[32] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI '97)*. Association for Computing Machinery, New York, NY, USA, 234–241. DOI: http://dx.doi.org/10.1145/258549.258715

[33] James E Kelly, Marcus J Sanchez, and Lawrence E Van Kirk. 1973. An assessment of the occlusion of the teeth of children 6-11 years, United States. (1973).

[34] Konstantina Kilteni, Jean-Marie Normand, Maria V. Sanchez-Vives, and Mel Slater. 2012. Extending Body Space in Immersive Virtual Reality: A Very Long Arm Illusion. *PLOS ONE* 7, 7 (07 2012), 1–15. DOI: http://dx.doi.org/10.1371/journal.pone.0040867

[35] T. A. Kuiken, G. A. Dumanian, R. D. Lipschutz, L. A. Miller, and K. A. Stubblefield. 2004. The use of targeted muscle reinnervation for improved myoelectric prosthesis control in a bilateral shoulder disarticulation amputee. *Prosthetics and Orthotics International* 28, 3 (2004), 245–253. DOI: http://dx.doi.org/10.3109/03093640409167756

[36] JAMES R. LACKNER. 1988. SOME PROPRIOCEPTIVE INFLUENCES ON THE PERCEPTUAL REPRESENTATION OF BODY SHAPE AND ORIENTATION. *Brain* 111, 2 (04 1988), 281–297. DOI: http://dx.doi.org/10.1093/brain/111.2.281

[37] Martin Lavallière, Lisa D'Ambrosio, Angelina Gennis, Arielle Burstein, Kathryn M. Godfrey, Hilde Waerstad, Rozanne M. Puleo, Andreas Lauenroth, and Joseph F. Coughlin. 2017. Walking a mile in another's shoes: The impact of wearing an Age Suit. *Gerontology & Geriatrics Education* 38, 2 (2017), 171–187. DOI: http://dx.doi.org/10.1080/02701960.2015.1079706 PMID: 26735083.

[38] Sang-won Leigh, Timothy Denton, Kush Parekh, William Peebles, Magnus Johnson, and Pattie Maes. 2018. Morphology Extension Kit: A Modular Robotic Platform for Physically Reconfigurable Wearables. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '18)*. ACM, New York, NY, USA, 11–18. DOI: http://dx.doi.org/10.1145/3173225.3173239

[39] Sang-won Leigh and Pattie Maes. 2016. Body Integrated Programmable Joints Interface. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 6053–6057. DOI: http://dx.doi.org/10.1145/2858036.2858538

[40] Lorraine Lin, Aline Normovle, Alexandra Adkins, Yu Sun, Andrew Robb, Yuting Ye, Massimiliano Di Luca, and Sophie Jörg. 2019. The Effect of Hand Size and Interaction Modality on the Virtual Hand Illusion. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (2019), 510–518.

[41] Sally A. Linkenauger, Heinrich H. Bülthoff, and Betty J. Mohler. 2015. Virtual arm's reach influences perceived distances but only after experience reaching. *Neuropsychologia* 70 (2015), 393 – 401. DOI: http://dx.doi.org/https://doi.org/10.1016/j.neuropsychologia.2014.10.034

[42] Sally A. Linkenauger, Markus Leyrer, Heinrich H. Bülthoff, and Betty J. Mohler. 2013. Welcome to Wonderland: The Influence of the Size and Shape of a Virtual Hand On the Perceived Size and Shape of Virtual Objects. *PLOS ONE* 8, 7 (07 2013). DOI: http://dx.doi.org/10.1371/journal.pone.0068594

[43] Sally A Linkenauger, Veronica Ramenzoni, and Dennis R Proffitt. 2010. Illusory shrinkage and growth: body-based rescaling affects the perception of size. *Psychological science* 21, 9 (09 2010), 1318–1325. DOI: http://dx.doi.org/10.1177/0956797610380700

[44] Sally A. Linkenauger, Jessica K. Witt, and Dennis R. Proffitt. 2011. Taking a hands-on approach: Apparent grasping ability scales the perception of object size. *Journal of Experimental Psychology: Human Perception and Performance* 37, 5 (2011), 1432–1441. DOI: http://dx.doi.org/10.1037/a0024248

[45] Matthew R. Longo and Patrick Haggard. 2010. An implicit body representation underlying human position sense. *Proceedings of the National Academy of Sciences* 107, 26 (2010), 11727–11732. DOI: http://dx.doi.org/10.1073/pnas.1003483107

[46] Lara Maister, Mel Slater, Maria V. Sanchez-Vives, and Manos Tsakiris. 2015. Changing bodies changes minds: owning another body affects social cognition. *Trends in Cognitive Sciences* 19, 1 (2015), 6 – 12. DOI: http://dx.doi.org/https://doi.org/10.1016/j.tics.2014.11.001

[47] Angelo Maravita and Atsushi Iriki. 2004. Tools for the body (schema). *Trends in Cognitive Sciences* 8, 2 (2004), 79 – 86. DOI:http://dx.doi.org/https://doi.org/10.1016/j.tics.2003.12.008

[48] A Maravita, C Spence, and J Driver. 2003. Multisensory integration and the body schema: Close to hand and within reach. *Current biology : CB* 13, 13 (2003), R531–R539. DOI: http://dx.doi.org/10.1016/S0960-9822(03)00449-4

[49] Marie Martel, Lucilla Cardinali, Alice C Roy, and Alessandro Farnè. 2016. Tool-use: An open window into body representation and its plasticity. *Cognitive neuropsychology* 33, 1-2 (02 2016), 82–101. DOI: http://dx.doi.org/10.1080/02643294.2016.1167678

[50] Jared Medina and H Branch Coslett. 2010. From maps to form to space: touch and the body schema. *Neuropsychologia* 48, 3 (02 2010), 645–654. DOI:http://dx.doi.org/10.1016/j.neuropsychologia.2009.08.017

[51] Luke E. Miller, Matthew R. Longo, and Ayse P. Saygin. 2014. Tool morphology constrains the effects of tool use on body representations. *Journal of Experimental Psychology: Human Perception and Performance* 40, 6 (2014), 2143–2153. DOI: http://dx.doi.org/10.1037/a0037777

[52] Luke E Miller, Luca Montroni, Eric Koun, Romeo Salemme, Vincent Hayward, and Alessandro Farnè. 2018. Sensing with tools extends somatosensory processing beyond the body. *Nature* 561, 7722 (Sept. 2018), 239–242. DOI: http://dx.doi.org/10.1038/s41586-018-0460-0

[53] S. Nakagawara, H. Kajimoto, N. Kawakami, S. Tachi, and I. Kawabuchi. 2005. An Encounter-Type Multi-Fingered Master Hand Using Circuitous Joints. In *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*. 2667–2672. DOI: http://dx.doi.org/10.1109/ROBOT.2005.1570516

[54] Jun Nishida, Soichiro Matsuda, Mika Oki, Hikaru Takatori, Kosuke Sato, and Kenji Suzuki. 2019. Egocentric Smaller-person Experience Through a Change in Visual Perspective. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 696, 12 pages. DOI: http://dx.doi.org/10.1145/3290605.3300926

[55] Jun Nishida and Kenji Suzuki. 2017. bioSync: A Paired Wearable Device for Blending Kinesthetic Experience. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 3316–3327. DOI: http://dx.doi.org/10.1145/3025453.3025829

[56] Jun Nishida, Hikaru Takatori, Kosuke Sato, and Kenji Suzuki. 2015. CHILDHOOD: Wearable Suit for Augmented Child Experience. In *Proceedings of the 2015 Virtual Reality International Conference (VRIC '15)*. ACM, New York, NY, USA, Article 22, 4 pages. DOI:http://dx.doi.org/10.1145/2806173.2806190

[57] Nami Ogawa, Takuji Narumi, and Michitaka Hirose. 2017. Distortion in Perceived Size and Body-based Scaling in Virtual Environments. In *Proceedings of the 8th Augmented Human International Conference (AH '17)*. ACM, New York, NY, USA, Article 35, 5 pages. DOI:http://dx.doi.org/10.1145/3041164.3041204

[58] Ottobock. 2019. Prosthetics. (2019). https://www.ottobockus.com/prosthetics/

[59] Tabitha C. Peck, Sofia Seinfeld, Salvatore M. Aglioti, and Mel Slater. 2013. Putting yourself in the skin of a black avatar reduces implicit racial bias. *Consciousness and Cognition* 22, 3 (2013), 779 – 787. DOI: http://dx.doi.org/https://doi.org/10.1016/j.concog.2013.04.016

[60] Dennis R. Proffitt. 2013. An Embodied Approach to Perception: By What Units Are Visual Perceptions Scaled? *Perspectives on Psychological Science* 8, 4 (2013), 474–483. DOI: http://dx.doi.org/10.1177/1745691613489837 PMID: 26173124.

[61] S. Qin, Y. Nagai, S. Kumagaya, S. Ayaya, and M. Asada. 2014. Autism simulator employing augmented reality: A prototype. In *4th International Conference on Development and Learning and on Epigenetic Robotics*. 155–156. DOI: http://dx.doi.org/10.1109/DEVLRN.2014.6982972

[62] Melissa N Richards, Diane L Putnick, Joan TD Suwalsky, and Marc H Bornstein. 2020. AGE DETERMINATION GUIDELINES: Relating Consumer Product Characteristics to the Skills, Play Behaviors, and Interests of Children. (2020).

[63] G. P. Rosati Papini, M. Fontana, and M. Bergamasco. 2016. Desktop Haptic Interface for Simulation of Hand-Tremor. *IEEE Transactions on Haptics* 9, 1 (Jan 2016), 33–42. DOI: http://dx.doi.org/10.1109/TOH.2015.2504971

[64] MHD Yamen Saraiji, Tomoya Sasaki, Kai Kunze, Kouta Minamizawa, and Masahiko Inami. 2018. MetaArms: Body Remapping Using Feet-Controlled Artificial Arms. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*. ACM, New York, NY, USA, 65–74. DOI: http://dx.doi.org/10.1145/3242587.3242665

[65] 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)*. ACM, New York, NY, USA, Article 16, 2 pages. DOI: http://dx.doi.org/10.1145/3084822.3084837

[66] Felix Schoeller, Philippe Bertrand, Lynda Joy Gerry, Abhinandan Jain, Adam Haar Horowitz, and Franck Zenasni. 2019. Combining Virtual Reality and Biofeedback to Foster Empathic Abilities in Humans. *Frontiers in Psychology* 9 (2019), 2741. DOI: http://dx.doi.org/10.3389/fpsyg.2018.02741

[67] Andrea Serino, Michela Bassolino, Alessandro Farnè, and Elisabetta Làdavas. 2007. Extended Multisensory Space in Blind Cane Users. *Psychological Science* 18, 7 (2007), 642–648. DOI: http://dx.doi.org/10.1111/j.1467-9280.2007.01952.x PMID: 17614874.

[68] Sotaro Shimada, Kensuke Fukuda, and Kazuo Hiraki. 2009. Rubber Hand Illusion under Delayed Visual Feedback. *PLOS ONE* 4, 7 (07 2009), 1–5. DOI: http://dx.doi.org/10.1371/journal.pone.0006185

[69] Alexa F. Siu, Son Kim, Joshua A. Miele, and Sean Follmer. 2019. ShapeCAD: An Accessible 3D Modelling Workflow for the Blind and Visually-Impaired Via 2.5D Shape Displays. In *The 21st International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '19)*. Association for Computing Machinery, New York, NY, USA, 342–354. DOI: http://dx.doi.org/10.1145/3308561.3353782

[70] Ana Tajadura-Jiménez, Domna Banakou, Nadia Bianchi-Berthouze, and Mel Slater. 2017. Embodiment in a Child-Like Talking Virtual Body Influences Object Size Perception, Self-Identification, and Subsequent Real Speaking. *Scientific Reports* 7, 1 (2017), 9637. DOI:http://dx.doi.org/10.1038/s41598-017-09497-3

[71] Alvin R. Tilley and Henry Dreyfuss Associates. 2001. *The Measure of Man and Woman: Human Factors in Design*. John Wiley & Sons.

[72] Koki Tamashiro Tomohiro Aka, Reyes Tatsuru Shiroku. 2011. SKELETONICS SUIT. (2011). https://ars.electronica.art/nextidea/skeletonics-suit/

[73] D. Tsetserukou, S. Hosokawa, and K. Terashima. 2014. LinkTouch: A wearable haptic device with five-bar linkage mechanism for presentation of two-DOF force feedback at the fingerpad. In *2014 IEEE Haptics Symposium (HAPTICS)*. 307–312. DOI: http://dx.doi.org/10.1109/HAPTICS.2014.6775473

[74] Björn van der Hoort and H Henrik Ehrsson. 2014. Body ownership affects visual perception of object size by rescaling the visual representation of external space. *Attention, perception & psychophysics* 76, 5 (07 2014), 1414–1428. DOI: http://dx.doi.org/10.3758/s13414-014-0664-9

[75] Björn van der Hoort and H. Henrik Ehrsson. 2016. Illusions of having small or large invisible bodies influence visual perception of object size. *Scientific Reports* 6 (06 10 2016), 34530 EP –. https://doi.org/10.1038/srep34530

[76] Björn van der Hoort, Arvid Guterstam, and H. Henrik Ehrsson. 2011. Being Barbie: The Size of One's Own Body Determines the Perceived Size of the World. *PLOS ONE* 6, 5 (05 2011), 1–10. DOI: http://dx.doi.org/10.1371/journal.pone.0020195

[77] A. Wege and G. Hommel. 2005. Development and control of a hand exoskeleton for rehabilitation of hand injuries. In *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 3046–3051. DOI: http://dx.doi.org/10.1109/IROS.2005.1545506

[78] J. P. Whitney, M. F. Glisson, E. L. Brockmeyer, and J. K. Hodgins. 2014. A low-friction passive fluid transmission and fluid-tendon soft actuator. In *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 2801–2808.

[79] J. P. Whitney, Tianyao Chen, J. Mars, and J. K. Hodgins. 2016. A hybrid hydrostatic transmission and human-safe haptic telepresence robot. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*. 690–695.

[80] Jessica K. Witt and Dennis R. Proffitt. 2005. See the Ball, Hit the Ball: Apparent Ball Size Is Correlated With Batting Average. *Psychological Science* 16, 12 (2005), 937–938. DOI: http://dx.doi.org/10.1111/j.1467-9280.2005.01640.x PMID: 16313656.

[81] Jessica K Witt and Dennis R Proffitt. 2008. Action-specific influences on distance perception: a role for motor simulation. *Journal of experimental psychology. Human perception and performance* 34, 6 (12 2008), 1479–1492. DOI: http://dx.doi.org/10.1037/a0010781

[82] Jessica K. Witt, Susan C. South, and Mila Sugovic. 2014. A perceiver's own abilities influence perception, even when observing others. *Psychonomic Bulletin & Review* 21, 2 (01 Apr 2014), 384–389. DOI: http://dx.doi.org/10.3758/s13423-013-0505-1

[83] Chris Woebken and Kenichi Okada. 2008. Animal Superpowers: Ant and Giraffe. (2008). https://www.moma.org/interactives/exhibitions/2011/talktome/objects/146222/

[84] F. Y. Wu and H. H. Asada. 2015. "Hold-and-manipulate" with a single hand being assisted by wearable extra fingers. In *2015 IEEE International Conference on Robotics and Automation (ICRA)*. 6205–6212. DOI: http://dx.doi.org/10.1109/ICRA.2015.7140070

[85] Nick Yee and Jeremy Bailenson. 2007. The Proteus Effect: The Effect of Transformed Self-Representation on Behavior. *Human Communication Research* 33, 3 (07 2007), 271–290. DOI: http://dx.doi.org/10.1111/j.1468-2958.2007.00299.x