Morphological Interfaces: On Body Transforming Technologies

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Abstract

A close integration of human and machine has been envisioned by researchers and artists for generations, however, there has been little effort in investigating the possibility and plausibility of the idea until recent years. We seek to open a discussion on how the notion of self is plastic, and how innately we are capable of empowering and extending ourselves through technologies. Neuroscience studies show using a tool not only offers new capabilities, but also reconstructs our cognitive architecture to include the tool as a part of ourselves. This adaptive nature of the body image poses an opportunity for designing interfaces that become natural extensions to us. In this paper we introduce previous studies drawn from various fields of study, and discuss the role of the body in the self-world relationship, body image plasticity, and how designing the body may affect neural developments. We also offer a categorization of related technologies, along with our current explorations. Finally, potential issues and challenges in realizing the presented form of interfaces are addressed.

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The Body is an Interface

> *"Each progressive step in the development of sensor and display technology moves telecommunication technology towards a tighter coupling of the body to the interface. The body is becoming present in both physical space and cyberspace. The interface is*

> *adapting to the body; the body is adapting to the interface"*
>
> — The Cyborg's Dilemma: Progressive Embodiment in Virtual Environments, Frank Biocca [9].

Conventional User Interface (UI) designs rely on users' innate skills, or their body image, regarding them as time-invariant. However, neuroscientific evidences show how a tool use leads to different paths of neural development. Skillful uses of the hand change the cortical activity representing the tactile receptors on fingertips [16, 17]. String instrument players have a stronger cortical activity in response to touch on the fifth digit than regular people [16]. A recent study showed that the cortical potentials from the thumb and index fingertips were directly proportional to the intensity of smartphone use [17].

> *"In viewing cognition as embedded or situated, embodied cognitive science emphasizes feedback between an agent and the world. We have seen that this feedback is structured by the nature of an agent's body...This in turn suggests that agents with different kinds of bodies can be differentiated in terms of degrees of embodiment...Embodiment can be defined as the extent to which an agent can alter its environment."*
>
> — Degrees of embodiment; The Routledge Handbook of Embodied Cognition, Michael Dawson [14]

Scientific studies suggest that a tool use induces change in how the brain processes the body image, therefore changing how one perceives the space around. When a macaque monkey uses a rake for collecting food, its visual receptive field was enlarged to a wider range [24]. A person using a stick for pointing perceives far as near [8]. Furthermore, Virtual Reality (VR) avatars of different sizes change how spacious the virtual space around feels [46].

What a person holds or what his/her body is not only changes the list of possible actions, but also redefines how the person perceives. The body and its extension form a link between an agent and the world, structuring the action/perception loop. Researchers conducted experiments with kittens [22], and proved that this body-world interplay is even more critical. Two kittens were put in an apparatus, both able to see, but only one of them was allowed to move the apparatus around. After series of exposure to the apparatus, it turns out that the one without the locomotive capability didn't show response to visual stimuli.

Recently, several researchers explore a more unorthodox possibility of having an alternative body. Homuncular Flexibility (HF) [49] is an idea conceived by Jaron Lanier and his collaborators out of accidentally generated non-human whole-body avatars during their early development of VR systems. In his and his collaborators' recent study [50], they report that participants were able to learn how to control avatars with a third arm or ones with legs and arms swapped. They adjusted their control strategies within a few minutes, and even became more efficient using some of the non-anthropomorphic avatars than a regular one. In short, the participants were able to adapt to the new bodies, where the new bodies unfold new action potentials.

Body Image Plasticity

HF describes the human brain plasticity that allows for remapping motor control to a different, non-anthropomorphic body. Since neural control has many clinical applications, researchers have long been exploring how to map brain signals to new motor control schemes. A notable example of remapping is an EEG driven robotic hand controlled by a monkey [47]. An electrode array was implanted in the right hemisphere — the same side as the robotic hand — meaning the monkey was able to develop a new command-control mapping. A similar study was done with human subjects, where a continuous use of a semi-arbitrary EMG controller can induce a newly developed muscle synergy [25].

Bach-y-Rita *et al.* [6] discussed the use of vibrotactile feedback on the back for the visually impaired. They report in their study that *"...subjects spontaneously report the external localization of stimuli, in that sensory information seems to come from in front of the camera, rather than from the vibrotactors on their back"*. This implies a system that makes new sensorimotor connections goes beyond simply giving new sensing capabilities; they can reconfigure the entire action-perception architecture of a user.

The brain's ability to adapt is not limited to motor control or sensing; the body image can be tweaked to include extra limbs or even change behaviors. In a recent Rubber Hand Illusion (RHI) study, it is shown that the sensation of having a third arm can be induced [19] through tactile stimulation. Test participants reported they had the sensation of being touched at two spots, when both their hand and the rubber hand were touched. Giving users VR avatars with different traits such as gender [28], body shape [39], or character [40] was shown to change their behaviors.

Design of Morphology

Numerous neuroscience studies suggest the plausibility of transforming our morphology through technologies, but it is more important to note what it would mean.

> *"Bodily shape (morphology) and bodily biomechanics reconfigure a wide variety of problems in ways that promote fluidity and efficiency by simplifying the neural commands required to bring about complex behaviours, effectively delegating aspects of control and processing to the body itself"*
>
> — Andy Clark, in one of his lectures

Not every muscle and joint of the human body is individually controlled through brain signals. An anatomical study [45] on the human forearm reveals that the tendon network acts like switches of a logic gate. In other words, an anatomical structure forms hardware circuits that *"synergistically interact with the nervous system to modify the interpretation of control signals"*. This concept is also adopted by the field of Embodied Robotics, where Pfeifer and Bongard [38] call this synergistic computation happening in the body as "morphological computation".

Guy Claxton [13] pushes the view, that the body takes a significant computing role, to another extreme.

> *"…that we are fundamentally built for action, not for thinking or understanding…. Thinking is a recently evolved tool for supporting smart action. We'll see that the brain evolved to help increasingly complicated bodies coordinate their interlocking sub-systems in the service of the whole community."*
>
> — Why Your Mind Needs Your Body Much More than It Thinks, Guy Claxton

In the movie *Gattaca*, there appears a genetically "defective" twelve-fingered pianist playing Schubert's Impromptu in G-flat major, Op. 90, No. 3. Aside the nice touch of adding extra notes to the original composition, it is known that there is a direct correlation between hand size/span and piano learning abilities [29]. We acquire skills by learning how to use our own hands, but the design of the hands also may define what we can or can't do. Although we need more fossil evidence to fully understand, the sophisticated manual skills and the brain size of Homo sapiens are known to have co-evolved [33, 48]. Corporeal and cognitive capabilities may as well be byproducts of each other.

Baumer *et al.,* in their alt.CHI paper [7], discuss a series of speculative research topics in the future. One of the scenarios illustrates a research on touchscreen usage with more than ten fingers. Although extra finger implants may not be the most effective way for typing on touchscreens, it hints at a critical step towards seeing the human body as part of interface design. A part of their report comes as: *"…found out that the optimal finger count is 12.5, with 6 normal-sized fingers on each hand and the dominant hand having an extra half-sized finger that can be moved with 6 DoF"*. Another scenario written by Andy Clark [11] suggests a more holistic version of the story — touching on hardware customization, interfacing with the nervous system, and policies around human augmentations. Now, 13 years after his book was published in 2003, ideas similar to the ones in his scenario are realized in research projects such as the 7-finger robot [51] or *FingerReader* [41].

> *"It's a cool prosthesis, since I've ordered some extras, such as a sixth finger (which, once I learn to control it, might help my guitar playing: who knows?), a lock-in putting grip (still illegal according to the PGA, but what the hell), and a built-in fingertip infrared camera capable of directly stimulating my optic nerve to allow me to "point and see" in the dark."*
>
> — Natural-Born Cyborgs: Minds, Technologies, and the Future of Human Intelligence, Andy Clark

Morphological Interfaces in Research

There are various artists including Stelarc and Rebecca Horn that explored the idea of an alternative body. Stelarc presented *The Third Arm* [4], a robotic contraption worn on the artist's body, and was able to control the third arm using muscles around his abdomen. With three arms of his, two of his biological ones and the robotic one, he became capable of writing with all three concurrently. Through numerous pieces, such as *Pencil Mask* (1972) and Two Hands *Scratching Both Walls* (1974-1975), Horn attempts to provoke the wearer's senses and an awareness to the wearer's body overall. Scribblings through pencils mounted on a mask creates a reflection of the wearer's face. A glove with extended fingers makes one feel, touch, and grasp things without any effort, but always keeping a certain distance from the objects.

Now the visions of the artists, although not always posed in an optimistic way, are becoming accessible and realized. From neural prostheses to implantable electronics, the human body affords a design space where we can curate our ability, perception, and identity.

In this section, we discuss key categories of technologies that attempt to alter the morphological structure of users, thereby redefining what the body can do. The focus of this paper is on ones that relate to physical abilities, and the works listed in this section share the same scope (please refer to references in the previous section [28, 39, 40] for discussions on social or cognitive aspects).

By morphological interfaces, we address technologies that aim to modify the physical structure of the body (external morphology) or the sensorimotor/control mapping (internal morphology). The selected categories include: extension in series with body extremities, extension in the number of limbs, computationally manipulating the body, and (re-)mapping sensory streams to motor capabilities.

Series-limb Exoskeletons
Series-limb exoskeletons [3, 15, 23] are a type of exoskeletons that are designed to be connected with a user in series. They often extend along the limbs and attribute body extremities with new properties. A classic example would be the exoskeleton developed in the 60s by GE, a motorized gripper-like glove, that gives extra strength to its wearers. Series-limb exoskeletons are not limited to giving literal extensions, and may as well provide new physical properties (e.g. stiffness, adhesiveness) to body extremities.

PowerSkip [3] is a pair of elastic leg extensions that allows a user to jump much higher than regular people. *SpringWalker* [15] is a pantograph-like motorized contraption designed to help users travel faster with improved metabolic efficiency. Gecko-inspired climbing gloves [21] enable climbing on vertical walls with palm surfaces engineered to stick on walls.

Supernumerary Robots
Supernumerary Robots (SR) [31, 37, 51] is a field in robotics that investigates the use of wearable robotic fingers or limbs working in tandem with users. Unlike traditional wearable robots, such as exoskeletons or prostheses, SRs are designed as independently moving appendages that collaborate with a user "side-by-side". In the past few years, several SR systems have been proposed: SR fingers [51], SR arms [18, 31], and SR legs [37].

The SR drumming system developed by Georgia Tech [18] allows drumming with three arms. The system utilizes a Brain-Computer Interface for selecting which drum a robotic arm plays. Then a software analyzes the music being played by a human user, generating beats to be played by the robotic arm. SR fingers [51] by MIT facilitates synergy between the seven fingers (5 biological + 2 robotic fingers), steering the motions of two additional robotic fingers to follow the overall shape of the hand. Shoulder mounted SR arms [31] learn how to collaborate with a user through demonstration,

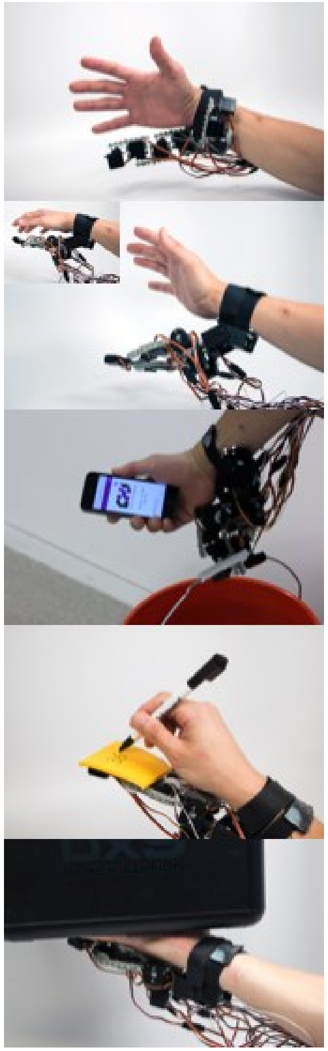

Figure 1: (from top to bottom)
1) sixth finger configuration,
2) second palm configuration for grabbing large objects,
3) the robotic fingers offloading tasks,
4) taking a note with a single hand,
5) strength amplifying configuration.

proactively taking actions based on predictive inference on the user's actions.

Computational Manipulation of the Body
Instead of extending or adding limbs, existing limbs can also be used as a computational medium. Electrical Muscle Stimulation (EMS) has been widely used in HCI as a means of controlling the human body. Researchers have explored using the human body as a surrogate for teleoperation [44]. *Muscle-plotter* [32] utilizes EMS for actuating forearm muscles in order to assist in drawing 2-D graphs. In the system, a user moves the pen horizontally, while electrical stimulations induce vertical movements to create y-values. In effect, the user and computer algorithm share the control of the user's body. *Inferno* [2] presents a synchronized set of exoskeleton suits, where their wearers are forced to dance in synchronization.

Sensorimotor Retargeting
As discussed earlier in the paper, Bach-y-Rita's report [6] offers a critical insight into how a new sensor-motor relationship can be constructed. This helps identifying a type of sensory augmentation that redefines how sensory input/output is tied with motor actions.

FingerReader [41] presents a similar, but mobile, system that allows users to read text through a camera worn on a finger. The configuration, unlike automatic text recognition via head mounted cameras, affords the ability to take active roles in reading activities. Hameed *et al.* explored the subdermal implantation of a magnet on the fingertips [20]. Ishin-Den-Shin [1] is a wrist-worn transducer that sends audio through the hand, thereby, one can direct audio messages to a specific person through direct finger contact with his/her ear.

Designing Morphological Interfaces

The type of human augmentation technology discussed in this paper would be often designed to be always-available. Therefore, it would be required to offer a certain level of versatility and the ability to blend in with users' habits. On a related note, Jarvenpaa and Lang [26] discusses mobile technologies' "always on" aspect, summarized as eight paradoxes. Out of those eight paradoxes, the four most relevant ones are *empowerment/enslavement, independence/dependence, competence/incompetence, and fulfill needs/create needs*. Based on SR finger implementations we have explored, we present some discussion points and our prototypes and applications as preliminary examples.

Synergy
An empowering technology offers more capabilities to its users, however, it also often enforces the use of the technology (*dependency*) or even nudges the user to take certain actions (*enslavement*). Science fiction literature also tends to capture the phenomena as a dystopian element [10], where human capability is substituted by machines. Especially if a "substitutional" technology taps into the basis of what our body is, or what we are, a fail-prone design may lead to catastrophic consequences. It is then important for such a technology to form a synergy with us, rather than replacing or hindering our innate abilities.

In light of the discussion above, we have examined potential "synergistic" applications of a body-worn robotic device that gives additional finger-like appendages [30] (figure 1). We implemented a series of applications that showcases how biological fingers and robotic fingers can synergistically operate. The robot becomes an effective assist in holding a large object, executing multiple tasks at the same time, offering better strength, and so on (figure 1). These applications are designed in a way that a user takes a more dominant role, while the robotic fingers take supportive roles working in parallel with the user. Please refer to [30] for more details.

Customization and Easy Disengagement
An efficiency obtained through a technology may lead to a sense of developed incompetency. For example, relying on electronic memory may impose a compromising effect on one's own memory (*incompetency*). In addition to that, a new technology demands extra works, such as maintenance or carrying, users didn't have before (*create needs*). On a related note, it is reported that the burden of extra work/maintenance and activity (or need) change were main abandonment rationales of wearable devices [12, 27].

To address those issues, a technology that is easy to tailor for versatile needs, or that is easily disengaged would be desirable. We have been developing another version of the robotic joints system that allows easy customization and disengagement. With a modular hardware kit that consists of various actuator, sensor, and end-effector blocks, a user can daisy chain different blocks to build one's own body-worn augmentations (figure 2). We also designed a separate attachment module (or a wrist module) so that the robotic construction can be disengaged (and individual modules put in a small pocket) when not needed.

Figure 2: (from top to bottom)
1) designed modular components,
2) assembly of the modules,
3) assembled robotic configuration
4) mounted on the attachment module,
5) customized end-effectors,
6) a robotic configuration in action.

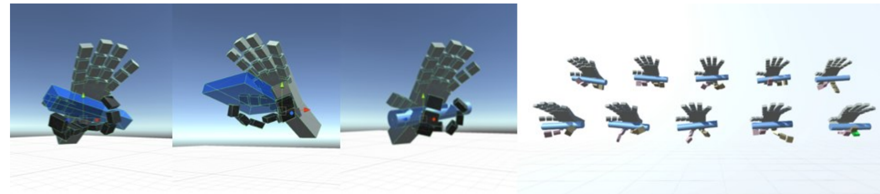

Figure 3: (left) object gripping strategies inferred by our simulation algorithm, (right) genetic algorithm generates a population of robots with varying assembly, and scores how well each assembly can adapt to the list of tasks given

Potentially, the generation of robotic configurations can be automated using self-assembly technologies [42, 52]. But in the near future, a software program can guide the user on how to build a robot to acquire certain capabilities, therefore, the user is no longer responsible for building an optimal configuration. We have developed an experimental evolutionary algorithm, where the software simulates a given task with a batch of different robotic construction to find optimal morphology and control strategies (figure 3).

Potential Discussion and Challenges

In this section, we discuss non-technical topics related to morphology-extending technologies, addressing potential challenges in deployment beyond the scope of this paper. The topics here are selected to open further discussions in the community, rather than drawing definitive conclusions.

Identity
Globalization and rapid dissemination of information through mobile computing have accelerated paradigm change in personal or cultural identities [34]. It is not trivial what a high programmability of the body will bring, and how an augmentation as identity would interact with age, race, gender, ability or cultural

norms. Accessibility to the means of modifying what is given as a biological marker, and the wide availability of technology, may accelerate the globalization of identity even further.

On the other hand, researchers suggest that the high accessibility to services via mobile devices facilitated personalization [43], or a new hybrid of globalization and localization [34]. In fact, it is only recent the body has become integral to our identities, as "the body has moved away from the sphere of nature into the sphere of culture" [35]. A potentially critical discussion here may be how to find a balance between offering optimized necessities and enabling personalization as vanity, given the technological developments hinting at the future where people can "design" themselves.

Self-Attribution
As body-worn, or –implanted, technologies become more accessible, a more in-depth study on self-attribution to those technologies will be required. Researchers have investigated what constitutes to the body ownership [5], however, the studies are largely limited to static objects or virtual graphics. Many parameters such as weight, elongated use, controller design, feedback modality, and so on, are yet to be studied.

Interfacing with the Human Nervous System
A critical technical challenge in realizing a true body extension device is establishing low-level connection between the nerves and the device. Although a lot of progress in neural control has been made in the field of robotics, still numerous problems remain unresolved — including acquisition of stable/precise control signals and neural feedbacks - e.g. tactile sensation, proprioception.

A notable clinical case recently reported is the implantation of an ossointegrated prosthetic arm [36]. The implantation is done through a surgical procedure that interfaces the prosthesis directly to the remaining bone structure of an amputated part of the arm. The procedure allows connecting electrodes directly to the peripheral nervous system, which makes EMG signal acquisition robust to environmental noise. In addition to that, the participant was able to chronically recover tactile perception through electrical stimulation to nerve bundles despite long-term amputation (>10 years). Although such an invasive procedure is not widely accessible at the moment, with such techniques of connecting our nerves to machines becoming more robust and available, the more plausible blurring the boundary of the body will become.

Conclusion
In this paper, we discussed neuroscience and cognitive science studies, in order to investigate the plausibility of body transforming (or morphological) interfaces. The body plays an integral role in mediating the interaction between the self and the world. Therefore, a technology that extends or transforms the body may lead to overall changes in physical ability, perception, and cognition. Based on existing technologies aiming to transform the human body, we discussed four categories of morphological interfaces: series-limb exoskeletons, supernumerary robots, computational manipulation of the body, and sensorimotor retargeting. We also illustrated design issues and potential challenges, accompanied by examples developed with our wearable robotic joints systems.

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