Creating small wearable devices full of sensors is becoming increasingly easy, but how can we pack strong mechanical actuation into such tiny packages? Here, we argue that Electrical Muscle Stimulation (EMS) might be the way to go.

EMS devices use a signal generator and electrodes attached to the user’s skin to send electrical impulses to the user’s muscles. This causes the muscles to contract involuntarily, thereby letting the device actuate the user’s limbs. Although EMS devices have been used in rehabilitation medicine since the 1960s to regenerate lost motor functions, only in the last few years have researchers started to experiment with EMS to create interactive systems. For example, researchers have explored using EMS as a means for teaching users how to play a new musical instrument, administering walking directions, receiving information from computing devices without a screen, and increasing realism and immersion in virtual experiences. Many of these projects exploit the fact that EMS miniaturizes well, which is why it lends itself to pervasive computing use cases, particularly those involving mobile and wearable devices. Furthermore, as we discuss here, EMS provides researchers with the technical means to create devices even smaller than current wearable devices.

**ELECTRICAL MUSCLE STIMULATION**

Figure 1 shows an example of using EMS to add realism to an experience. In this case, we mounted a custom EMS signal generator to the back of a mobile phone. It connects to the user’s palm flexor muscles using one pair of electrodes per forearm. The resulting device connects to the phone via Bluetooth, letting apps on the phone actuate the user’s wrists. When the electrode pair on the user’s left arm is activated, for example, the user’s left wrist contracts involuntarily and tilts the device in the user’s hand to the right (as shown in the figure). At all times, operation is comfortable and pain-free.

Figure 1. Our prototype electrically stimulates the user’s arm muscles via electrodes, causing the user to involuntarily tilt the device. As he is countering this force, he perceives force feedback.
In this particular example, we use the device to add force feedback to a game. This game requires users to steer an airplane by tilting the device left and right, but there are strong side winds that threaten to push the plane off course. In the situation shown in Figure 1, the device renders winds coming from the left by stimulating the user’s left wrist muscles, tilting the mobile device to the right—against the user’s will. To stay on course, users must counter the “wind” forces by pushing back using their other wrist. Users are thus effectively fighting their left wrist, which is under the control of the application, using their right wrist. In one of our experiments, we had participants compare the game as played with our EMS-based device versus with vibrotactile feedback (found in any smartphone). Users reported that the muscle stimulation effect of our device depicted a more realistic experience.

EMS ACTUATION VS. MECHANICAL ACTUATION

This simple prototype shown in Figure 1 is just one of several projects we built to explore creating interactive systems based on EMS. Here, we note how EMS compares to more traditional approaches involving mechanical actuators.

EMS Is Considerably Smaller

The prototype we just presented focuses on what we view as a core benefit of EMS, which is that EMS miniaturizes well. The form factor of EMS-based devices tends to be considerably smaller than the more traditional approach of using mechanical actuators.

Figure 2 illustrates this point by showing how EMS-based devices eliminate the need for bulky hardware. While the mechanical approach tends to require not just actuators but also an exoskeleton that transmits forces to the right locations and with appropriate levers (Figure 2a), EMS-based systems achieve a similar effect by instead leveraging the skeleton already “built into” the user’s body (Figure 2b).

This is the result of a single central and very unique aspect of EMS systems: where mechanical solutions add mechanical components to the user’s body, EMS-based devices instead borrow “components” from the user—that is, the “mechanics” already contained in the human body. Ultimately, it is this ability to re-use parts of the human body that lets EMS-based devices lend themselves well to mobile and wearable applications.

EMS Closes the Haptic Loop in Wearables

Figure 3 shows another EMS-based device. Its functionality is similar in that it also senses and actuates the user’s wrist. However, while the previous device was designed for a mobile form factor, we designed this one for a wearable form factor: a self-contained armband that users wear under their sleeves.

In the spirit of wearable devices, this device is designed to let users focus on some other primary task, which means that, to keep distractions to a minimum, the device doesn’t feature a screen. We instead implement the device’s entire interaction based on haptics. We accomplish this as follows. First, in addition to flexing the user’s wrist, the device can also extend that same wrist using a second pair of electrodes. Second, we added the ability to sense the wrist’s position using an accelerometer ring.

Figure 3a shows a simple use case of this device in which the user controls video playback. The position of the user’s wrist is tightly coupled with the position of the video play head. As shown in Figure 3b, as the video plays, users find their wrist continuously flexing upward. The device achieves this by actuating the user’s wrist using EMS. At the same time, users can set the position of the play head by posing their wrist (Figure 3c).

EMS Scales Well to Full-Body Experiences

While the two prototypes just presented actuate only the user’s wrist, we also explored full body actuation to demonstrate that EMS scales well into more encompassing experiences. The prototype shown in Figure 4 uses EMS to...
simulate the resistance of walls and the weight of heavy objects in virtual reality. By actuating the user’s limbs with EMS, our systems prevent the user’s hands from penetrating virtual objects, effectively recreating the resistance of obstacles.

This prototype uses four electrode pairs on one side of the body, allowing it to actuate wrists, biceps, triceps, and shoulders. As before, the use of EMS allows for a wearable form factor—unlike the more traditional actuation, using pulley systems or exoskeletons.

As Figure 4 shows, when the user lifts a virtual cube, our system lets the user feel the weight of the whole cube and resistance of the cube’s facets. The heavier the cube and the harder the user presses the cube, the stronger a counter-force the system generates. Our system implements the physicality of the cube by actuating the user’s opposing muscles with EMS. By using this approach on different muscle groups, our system simulates a wide range of objects, including walls, shelves, buttons, and projectiles.

In addition to actuating the user’s upper body, we created a prototype that can be attached to various parts of the body, such as the user’s legs. Figure 5 shows this prototype, which is called Impacto because it was designed to render the haptic sensation of hitting and being hit. The key idea that allows the small and light Impacto device to simulate a strong punch is that it decomposes the stimulus: Impacto renders the tactile aspect of being hit by tapping the skin using a solenoid; it adds impulse to the hit by thrusting the user’s arm backwards using electrical muscle stimulation. Furthermore, as Figure 6 shows, because the device is a generic shape, users can also wear it on their legs to enhance the experience of kicking.

EMS Strengths and Limitations
The actuation and force feedback we demonstrated using EMS have traditionally been achieved using mechanical actuators.

In addition to miniaturizing well, one of the strengths of EMS-based systems is that they can reach parts of the human body that would be hard to actuate using other means. For instance, the EMS-based application Vibrat-o-matic assists novice users in singing in vibrato by stimulating muscles of their abdomen and larynx. Mechanical systems are hard to apply here, as they require at least two mounting points.

However, EMS-based actuation is subject to a range of limitations, as suggested by the fact that some application domains are predominantly approached using mechanical actuators. Teleoperation—the transmission of forces between two remote users—has been a flagship area for mechanical actuators since the early days of robotics. This is because the precision and speed required by these applications is currently only delivered by systems based on mechanical actuation. The
same holds for robotically assisted surgery and related applications. The reason that EMS-based systems tend to be much less precise is in part because of the layered nature of the human muscles. Because electrodes reach muscles only indirectly via the user’s skin, their position tends to shift when the user moves, making it hard to target specific muscles without affecting nearby muscle tissues.

Another strength of mechanical actuators is that they allow for quasi-arbitrary force output, which has allowed for high-power applications, such as exoskeletons that provide the wearer with super-human strength. EMS-based systems, in contrast, are always bound by the physical strengths of the user.

These observations indicate the opportunities for future work in EMS. On the hardware level, several improvements would be welcome to help apply EMS to high-precision applications: increase the robustness of electrode placement against variations in body posture, actuate with higher precision to generate more complex poses, and take into account the user’s voluntary motions by simultaneously sensing muscle tension while actuating. On a higher level, several utilities could help foster EMS research, such as automatic calibration methods, methods that simplify the placement of the electrodes, and techniques for embedding electrodes into textiles.

Finally, EMS-based systems are idiosyncratic cases of human-computer interfaces because the interface created by the EMS doesn’t become an extension of the body but rather is the body itself. Consequently, EMS-based systems entail a kind of human augmentation that is both invisible and well integrated with the user. Interacting through an EMS-based device feels “direct” because users simply move their bodies and feel their bodies being moved. This might open up new avenues for designing interactive systems to help people better learn physical tasks.

Figure 5. Impacto is a wearable that combines a solenoid and EMS to render the haptic sensation of being hit in a boxing simulator.

Figure 6. By wearing the Impacto device on the leg and foot, the user experiences the impact of kicking a virtual football.
ACKNOWLEDGMENTS

We thank our colleagues Sijing You, Alexandra Ion, Patrik Jonell, Lung-Pan Cheng, Sebastian Marwecki, Willi Müller, and Daniel Hoffmann for fruitful collaborations in creating these prototypes. All work involving voluntary participants was done with prior written consent and following the standards of the Hasso Plattner Institute.

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