EMS-Based Actuation and Mechanical Actuation: two sides of the same coin?

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Abstract
For the past six years, the HCI community has been exploring electrical muscle stimulation (EMS) as a means for creating interactive systems, such as to teach musical instruments, simulate the presence of rigid objects in virtual reality, or guide users while walking. However, looking at the field of haptics, we see systems based on mechanical actuators, such as exoskeletons and pulley systems that achieve similar functionality. In this article, we explore this analogy. We discuss the similarities, as well as the key differences between these two approaches. Is EMS' potential to pack force feedback into a wearable form-factor really the main differentiator?

Author Keywords
Proprioception; electrical muscle stimulation; wearable;

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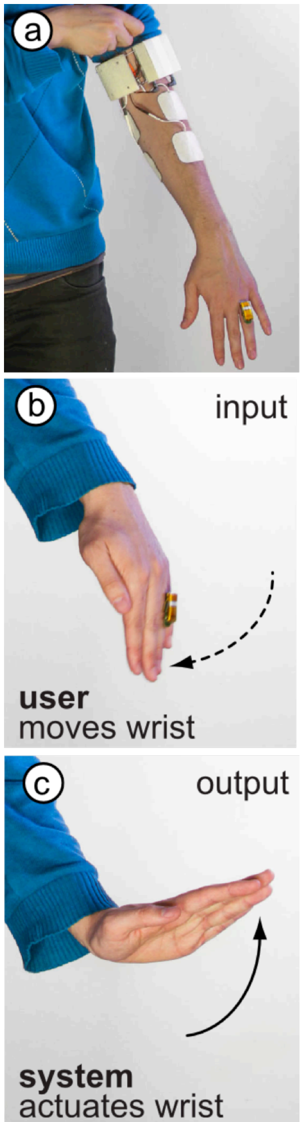

Figure 1: An example of an EMS-based interactive device that turns proprioception in an I/O channel [40].

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation]: User Interfaces - Interaction styles;

Introduction
For the past six years, the HCI community has been exploring electrical muscle stimulation (EMS) as a means for creating interactive systems. Applications tend to fall into three main areas: (1) immersion, such as simulate collisions in the virtual reality (e.g., *Impacto* [39]); (2) information access: as platform for I/O (see Figure 1) or guiding users while walking [32]; and (3) Training, such as to teach musical instruments, (e.g., *PossessedHand* [12]).

However, when looking at the related field of haptics [19,52], we find an analogy between human actuation based on EMS or on mechanical actuators (e.g., exoskeletons) as both approaches achieve a similar resulting effect, i.e., apply a force to the user's body. Figure 2 illustrates this analogy: both approaches produce a similar resulting effect: *limb displacement*.

To illustrate this further, we draw parallels between the two approaches using concrete examples: *Gesture Output* [1] actuates the users fingers via a clear sheet pulled by motors, while *Muscle-Plotter* [41] achieves a similar effect using EMS. *Third Hand* [56] uses a

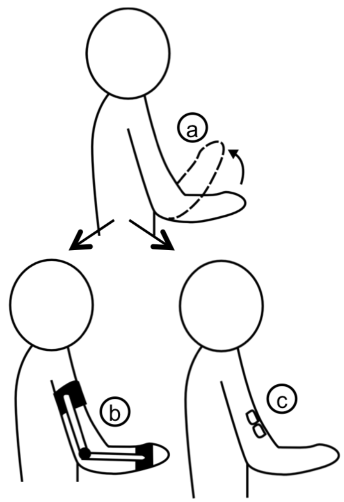

Figure 2: (a) Limb displacement can be achieved e.g., using (b) mechanical actuators or (c) EMS.

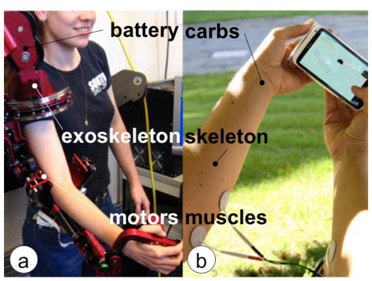

Figure 3: Analogy between the hardware components that make up a (a) mechanical actuator (here an exoskeleton [8]) and (b) an EMS-based actuator [38].

forearm-mounted robotic arm to provide force-feedback to a mobile phone, while *Muscle Propelled Force Feedback* [38] achieves this effect based on EMS.

Also, "under the hood" EMS and mechanical actuators are quite similar, which is illustrated in Figure 3. The typical EMS hardware is comprised of a *stimulation unit* and an *electrode pair;* these electrodes sit on the user's skin and deliver the electrical impulses, these cause the muscle to contract involuntarily and hence, move the user's limb. Similarly, mechanical actuators, such as exoskeletons, are comprised of four elements: a *motor driver* (e.g., a microcontroller), a *motor*, a *link* (between the motor and the user's limb) and an *attachment* to the user's limb.

So to what extent does are these two technologies interchangeable? In the following we take a closer look at the two approaches, i.e., actuation based on EMS and mechanics. We discuss the similarities, as well as the key differences between these two approaches.

Main applications of EMS

Replacement of human motor functions: In the 60s, EMS originated in the field of rehabilitation medicine. It aims at helping patients that lost motor functions (e.g., as a result of spinal cord injury) [53]. Most of the applications artificially induce body movements, such as grasping [24], walking [44], swallowing [47] and standing upright [15].

Teleoperation: Twenty years later, artists started to explore EMS in interactive art works. The early works of Stelarc [51,3] depicts examples of a simplified and early form of teleoperation between a human arm (moved by EMS) and a robotic arm. Similarly, the artwork of Manabe demonstrates the transfer of facial expressions between two users using EMG & EMS [28].

Only recently, EMS was used for interactive purposes by researchers in human-computer interaction. This has been clustered around three themes:

Training: In *PossessedHand* [12], EMS was employed as an output system to learn haptic tasks such as playing a string musical instrument. Similarly, EMS has been used to teach rhythmic patterns [4].

Immersion: The first interactive applications of EMS in revolved around gaming [16, 14]. These EMS-based haptic interfaces provided stronger sensations than the traditional vibrotactile feedback. In fact, researchers showed how EMS effectively miniaturizes force feedback, making it available, for instance, in mobile devices [38]. These, EMS-driven physical sensations increase the realism of interactive virtual environments. For example, EMS counter-forces enable users to feel the resistance of walls or the weight of objects in virtual reality (VR) [43]. Also, combined EMS and tactile stimuli simulates the sensation of hitting or being hit in VR [39].

Information Access: By adding input to EMS-based systems researchers closed the I/O loop. Hence, providing a platform for information I/O [40]. This idea, denoted as *Proprioceptive Interaction* (i.e., using poses of the both for input & output) allows users to interact eyes-free. This principle has been applied to, for example: allowing everyday objects to communicate their usage (*Affordance++* [42]) and for systems that communicate walking directions [32] or incoming data [49,13]. Lastly, by persisting the EMS output (e.g., as a physical trace, using a pen on a paper), we see also a new generation of EMS-based interactive systems that aims at supporting sensemaking [41].

Main applications of mechanical actuation

Interestingly, as summarized by Figure 4, we find that to some extend all these application scenarios have been first explored using mechanical actuators.

	EMS	Mechanical
Teleoperation	1995 [51] (in art)	1948 [46]
Replacing motor functions	1979 [53]	1969 [36]
Information Access	2015 [40, 42, 32]	1973 [50]
Training	2011 [12]	1980 [10]
Immersion	2006 [14]	1992 [6]

Figure 4: Summary of research in EMS and mechanical actuators in the different haptic domains [52]. (Dates represent earliest findings to the best of our knowledge)

Replacement of motor functions: besides early stationary machines for assisted rehabilitation [10], exoskeletons are popular for gait regeneration [27].

Teleoperation: precisely transmitting forces between two remote users [55,19,52]. In fact the first teleoperator robotic manipulators, such as the *GROPE IIIb* [17], were the precursors to today's desktop haptic systems (such as the Phantom [30]) and their functionality remains "unchanged" [52].

Information access: between users and computers (or other users) was also facilitated by means of mechanical actuators such as force feedback [50].

Training: systems use haptics to enhance learning of physical tasks such as palpation training [31].

Immersion: early force feedback devices were applied for increasing realism of virtual experiences [6]. Other popular mechanical designs for immersive feedback are pulley systems (e.g., SPIDAR [35] or SPIDAR-W [25]).

Is Mechanics interchangeable with EMS?

At this point one might wonder: *if an application was previously implemented using a mechanical-based actuator, can it then be replicated by means of EMS?*

Not necessarily. There are two main advantages of mechanical actuators: extra power and precision.

Mechanical actuators are more precise and reliable and hence are used for precise applications such as robotically assisted surgery [37]. In contrast, current EMS-based systems, are more imprecise due to: (1) the layered nature of the human muscles (on-skin electrodes cannot target a specific layer [34]); and, (2) the competition between user's own muscle tension and the EMS induced contractions. Resulting challenges in terms of improving EMS include:

1. Automatic calibration procedures (e.g., [29])
2. Electrodes that allow for embedding in textiles [23]
3. Higher precision (e.g., implanting electrodes [33]?)
4. Add muscle tension to the control loops (e.g., [22])

Exoskeletons can be more powerful than the human that carries it. In fact these were originally envisioned to achieve the effect that power assisted steering has in an automobile [52]. Since EMS uses the user's own muscles it cannot draw external power to supersede the user's strength.

Is EMS interchangeable with Mechanics?

So now we ponder on the reversed question: *if an application was implemented using an EMS system, can it then be replicated by means of mechanics?*

Not necessarily. There are two main advantages of EMS: it is mobile and it reaches more actuation sites.

EMS is mobile: in [38], we claimed that a key advantage of EMS is that it is capable of delivering strong force feedback in a mobile/wearable form factor. It is lighter and requires less energy than mechanical actuators. The low energy consumption of EMS-based systems comes from the fact that the *muscles* are our internal *motors*. Hence, the EMS needs only to provide a control signal to activate the muscle (as a motor driver does) but the power comes from inside the body. In fact exoskeleton-like actuators are an approach that is still "*confined to academic research labs and absent from commercial catalogues"* [52] due to their cost, complex infrastructure and limited practicality.

EMS reaches more actuation sites than mechanical actuators. As we've discussed EMS leverages the internal muscles and skeleton to directly actuate limbs. This enables EMS-based actuators to reach areas where we cannot envision how to mount the attachment to the mechanical actuator. For instance, *Vibr-o-matic* stimulates muscles of the abdomen and larynx to allow novice singers users to teach vibrato (amplitude modulation while singing) [48]. This actuation site would be hardly reachable with a mechanical actuator. To further exemplify sites not easily reached by mechanical actuators, EMS has been used to simulate food texture by actuating the jaw muscles [2].

EMS feels different than an exoskeleton. This might be another advantage of EMS but remains to be validated. The fact is: when moved by the exoskeleton an external force is what moves the user's limb. So the user mostly feels: *passive muscle stretch* [45] and *pressure* (caused the apparatus pushing against the user's limb). However, when moved by means of EMS: the *muscle stretch* is no longer passive, which means it is sensed by additional receptors that sense force (the Golgi Tendon organs) [45], but there is a new *tingling* sensation, caused by the electricity passing through the skin [7, 54].

To sum it up: we can now answer: *is EMS' potential to pack force feedback into a wearable form-factor really the main differentiator*? Yes, but EMS is not limited to that. It seems that EMS can be more than a smaller rendition of the mechanical approach, since it reaches more actuation sites and evokes different sensations.

Conclusions & Future Work

So are EMS and mechanical actuators two sides of the same coin? Our analysis above certainly points out a lot of similarities. In addition to our earlier observation that EMS-based interactive systems allow for smaller/wearable form factors, additional differences include: (1) the higher precision of mechanical actuators (2) EMS' ability to actuate areas otherwise unreachable using mechanical attachments.

As for future work, there may be other angles from which we can tackle this question, for instance: *what impact does EMS- and mechanically induced gestures have on user's sense of agency?* Answering this question might potentially impact the design of haptic training applications, such as guided learning [9,20].

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