On-Skin Technologies for Muscle Sensing and Actuation

Tim Duente, Max Pfeiffer, Michael Rohs
Human Computer Interaction Group
University of Hannover
{firstname.lastname}@hci.uni-hannover.de

Abstract
Electromyography (EMG) and electrical muscle stimulation (EMS) are promising technologies for muscle sensing and actuation in wearable interfaces. The required electrodes can be manufactured to form a thin layer on the skin. We discuss requirements and approaches for EMG and EMS as on-skin technologies. In particular, we focus on fine-grained muscle sensing and actuation with an electrode grid on the lower arm. We discuss a prototype, scenarios, and open issues.

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Introduction
In this paper we motivate and report on ongoing work regarding on-skin electrode grids for muscle sensing and stimulation (Figure 1). We describe a prototype, a number of scenarios it enables, and open issues in this area.

On-skin technologies exhibit a number of unique constraints that are difficult to meet with current technologies. Electromyography (EMG) and electrical muscle stimulation (EMS) use electrodes that are placed on the skin. EMG and EMS electrodes are flexible, relatively thin, and breathable to some degree. However, they are not yet comfortable to wear for longer periods of time and the use cycles are limited. The electrodes are reasonably robust. Both EMG and EMS are quite energy efficient. Thin and stretchable wearable prototypes of on-skin electrode and sensor systems are a subject of current research [7].

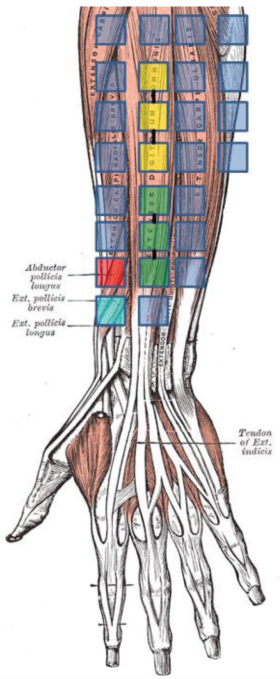

Figure 1: An EMS electrode grid covers several muscles and achieves high flexibility of actuation. Grouping the electrodes (yellow and green) reduces the sensation of the current. Several muscles can be actuated at the same time. Muscle background picture by Henry Vandyke Carter - Henry Gray (1918) Anatomy of the Human Body (See "Book" section below)Bartleby.com: Gray's Anatomy, Plate 418, Public Domain, https://commons.wikimedia.org/w/index.php?curid=27292

On-skin technologies offer the opportunity to implicitly sense biosignals, such as heart rate and electrodermal activity, which contributes to detecting bodily and emotional states. EMG measures the degree of muscle activation, which can be used to infer movement and muscle tension [1]. EMG has been used in commercial devices to recognize movement gestures[1].

On the output side, on-skin technologies may support different modalities: E-paper produces visual output, thin piezo elements produce auditory output, and coin motors produce vibrations. Haptic feedback is more challenging and can be realized through pneumatic compression feedback or electrical muscle stimulation.

EMS is particularly suitable for mobile haptic feedback, as it has low power consumption, does not require moving mechanical parts, and can be miniaturized considerably. EMS can produce a wide range of output, from light tactile feedback that is berely perceptible to strong force feedback that moves the user's limbs.

EMG and EMS as on-skin technologies provide continuous access to the underlying muscles, both in terms of sensing their state and actuating them. This is convenient for always-available haptic input sensing and output. As light EMS output is not observable it can provide a private and eyes-free feedback channel in public space, which, e.g., is beneficial for notifications.

It has been shown that EMS can achieve precise actuation of individual fingers of the hand [5]. EMS has also been used for target selection in virtual environments [4] and for guiding pedestrians [3]. However, fine-grained actuation requires multiple electrodes that can be individually controlled. Functional electrical stimulation has used electrode grids in a 2D arrangement [5]. Relevant considerations for designing EMS surface electrode grids include specifying the number, size, and spatial arrangement of the electrodes, the identification of the mapping of the stimulation to the effected movement, and the adaptation of signal strengths to changing physiological states.

Precise muscle actuation opens up a wide range of possibilities in augmented reality and ubicomp scenarios. These include gestural feedback when approaching an object, directional guidance, and enrichment of visual experiences. Tactile and haptic output may be connected to properties of the environment and user context. Advanced scenarios require a closed loop between actuation and sensing.

Electrode grids can be used to time-multiplex between EMS actuation and EMG sensing [6]. Novel forms of activity recognition may become possible in which, e.g., EMG senses an object that the user holds in hand and EMS slightly adjusts the posture to minimize fatigue.

Scenarios

We continue by describing three scenarios that may be enabled by combined EMS and EMG electrode grids.

Haptic notification and guidance

Alice puts on her smart-skin-electrode-grid-sleeve before leaving home. The sleeve generates a short calibration gesture to check whether it is well placed. She walks through the city as her hand performs a rotational gesture followed by a handshake code. From the movement she recognizes that it's her friend Bob who

[1] Thalmic Labs. Myo. www.myo.com

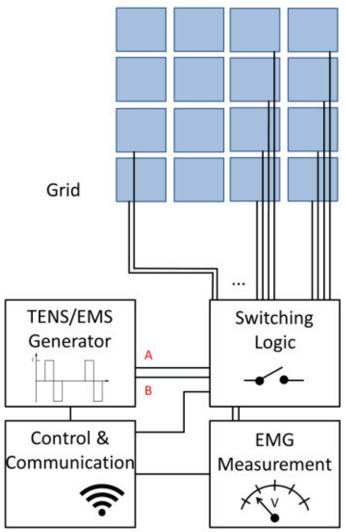

Figure 2: Components of the planned electrode grid. The EMS generator produces the stimulation signals, which are directed to different electrode configurations over the switching logic. A control and communication unit synchronizes the components. It controls the stimulation parameters and collects the measurements from the EMG unit.

happens to be nearby. She performs a "thumbs-up" gesture to indicate that she wants to meet him. Her hand guides her in the direction towards Bob. On the way she performs a "call" gesture to talk to Bob.

Movement learning in sports
Bob wants to improve his basketball skills. He puts on his smart sleeves, which senses his throwing motions and slightly corrects his movements. In the beginning he feels the sleeve's corrective action quite strongly. After a while he adapts his movements because of the haptic hints and notices that the feedback gets more subtle and that his throws get more precise.

Object detection
Carla's smart sleeve detects objects by the way she is holding them. The EMG sensors continuously measure the activation of the muscles in her lower arm. This activation pattern is then used to infer grasped objects and haptically display hints on the state and usage of these objects. An IMU provides information on posture.

On-Skin Electrode Grid Prototype

We propose a small device consisting of an EMS stimulus generator, an EMG measurement unit, and switching logic for an on-skin device (Figure 2). We are currently in the process of developing this device. Here we present the main design considerations.

The EMS stimulus generator should be able to produce ~20 channels for massively parallel fine-granular stimulation of lower arm muscles. Every channel should be adjustable in the following parameters: amplitude of the rectangle impulse and pulse duration. The frequency can be set in a range of 80 Hz to 100 Hz. Lower frequencies can result in muscle tremor, higher frequencies do not increase the strength of contraction. The 20 channels are generated with one EMS generator circuit via time multiplexing. For example to drive 20 channels at 100 Hz the generator will output signals at 2000 Hz and provide one pulse with 100 Hz to each output channel.

We suggest a grid of 80 electrodes to get a sufficiently fine control of the muscles. The electrodes should be small enough (e.g. 1x1 cm) to follow the form of the muscle (Figure 1). The ideal spatial arrangement results in a complete actuation of the targeted muscle and avoids stimulation of other muscles. Through the switching logic a set of electrodes can be merged to a large electrode. As shown in Figure 1 (orange and green), six electrodes overlap the muscle extensor digitorum. Also multi electrode settings become possible (Figure 1). The red and turquoise electrodes represent a second channel with different signal settings. With the presented system up to 20 different electrode configurations with different stimulation parameters can be used in parallel.

One aim of the grid is the reduction of the effort for electrode placement and calibration. It is necessary to provide a self-calibration function. We currently investigate three ways to realize this function: (1) EMG calibration measures calibration gestures, (2) optical tracking identifies finger positions, and (3) an IMU identifies finger and hand orientations.

To evaluate the prototype we will design an actuated gesture set that uses the full functionality of the electrode grid. The evoked movements will be measured and used to train an algorithm to link intended movements to activation patterns.

Open Issues

A number of open issues have to be addressed before the vision of a smart sleeve with an electrode grid for EMG sensing and EMS actuation may be realized.

Technical issues: How to control such a large number of electrodes? Subgroups of electrodes need to be configured freely. How to quickly switch between EMS and EMG? Existing approaches are described in [2,6]. How to guarantee safety?

Calibration and control: Machine-learning systems have to be designed that adapt to different physiologies and skin conductances. A fast identification of gesture mappings and comfortable signal levels is required.

Gesture and object recognition: Can we recognize gestures and grasped objects from EMG data and other sensor data? Can we recognize the weight of objects?

Acceptability: How do users interpret the actuated gestures? What conceptual models and metaphors may be employed? Are the generated gestures easy to learn? What electrode placements are acceptable?

Aesthetics: How to integrate the technology into clothes or jewelry and decoration to satisfy aesthetic needs of the users? How to design for long-term use?

Conclusions

We have motivated that haptic feedback is an important ingredient of on-skin technologies. EMS actuation and EMG sensing are particularly well suited as haptic technologies because they can be implemented as thin, flexible layers, provide unobservable output, and are relatively energy efficient. We have reported an initial prototype EMS electrode grid system that is currently under development. We formulated scenarios and open issues for on-skin haptic feedback.

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