Using Neuromuscular Electrical Stimulation for Pseudo-Haptic Feedback

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ABSTRACT

This paper focuses at the usage of neuromuscular electrical stimulation (NMES) for achieving pseudo-haptic feedback. By stimulating the motor nerves, muscular contractions can be triggered that can be matched to a haptic event. Reflecting an initial user test, we will explain how this process can be realized, by investigating the physiological processes involved. Relating the triggered feedback to general haptics, its potential in future interfaces will be identified and laid out in a development roadmap.

Categories and Subject Descriptors

H.5.1 [**Information Interfaces and Presentation**] Multimedia Information Systems — *artificial, augmented, and virtual realities*; H.5.2 [**Information Interfaces and Presentation**] User Interfaces — *Haptic I/O*; I.3.6 [**Computer Graphics**] Methodology and Techniques – *Interaction Techniques*; I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism—*Virtual Reality*

General Terms: Measurement, Performance, Design, Experimentation, Human Factors

Keywords: 3D User Interfaces, haptic feedback, neuroelectrical stimulation, biofeedback

1. INTRODUCTION

Within the medical and sports areas, the usage of electrical stimulation devices has been widely used for pain relief and muscular training. Transcutaneous electrical nerve stimulation (TENS) is generally applied to stimulate nerve endings in order to block pain [1], whereas neuromuscular electrical stimulation (NMES) is widely used for training muscles, both in the sports area and for rehabilitation purposes [5] [6], possibly aided by virtual reality aided methods [7]. Both methods are based on the electrical stimulation of nerves or receptors using impulses at different frequencies and intensities.

Only recently researchers have started to explore the usage of electronic stimuli for triggering somatic and kinesthetic events in human-computer interfaces. The somatic and kinesthetic systems handle the sensations that relate to force and touch. The somatic system perceives cutaneous (skin) and subcutaneous (below skin) sensations, whereas the kinesthetic system senses mechanical sensations in the joints and muscles. These sensations are generally known as haptic feedback and relate to the communication of information on geometry, roughness, slippage and temperature (touch), next to weight and inertia (force). Skin and muscle sensations are received by several receptors: thermoreceptors, nocireceptors, mechanoreceptors including proprioceptors and chemical receptors. Through electrical stimulation theoretically every kind of nerve or nerve ending, or receptor can be triggered, depending on the kind of stimulus provided to the user. These stimuli differ in pulse length, frequency, amplitude and triggering mode.

To provide neuroelectrical stimulation, electrodes are placed at the skin's surface. Implantable solutions or methods using needles also exist, but are not generally used yet. An electrical stimulus is able to reach a nerve or receptor due to the permeable properties of the tissues below the skin [2]. Under effect of specific ionic substances in cells, membrane potentials can be generated that have flown through the surrounding tissues. These potentials can eventually result in a pseudo-haptic event by stimulation of the motor nerves. The permeable characteristic of the skin tissues is also used for biopotential interfaces, by reading so called action potentials. An example of an interface using action potentials is the electromyographic (EMG)-based joystick by Jorgensen et al [3].

Till now, the majority of experiments have focused at providing tactile feedback by triggering specific receptors just below the skin (electrotactile feedback), whereas the triggering of muscles to simulate force related events has found hardly any application. Haptic systems examples are the hand-muscle oriented system by Folgheraiter et al applying a glove interface [8], the artistically oriented facial muscle stimulation system by Elsenaar and Scha [9], and the Mad Catz Bioforce, a controller prototype which delivered electric impulses to the user's forearms [10]. Elsenaar and Scha also reported on medical studies using electrical stimulation on corpses to generate muscle contractions in the 18th century. Electrical stimulation examples include the finger-mounted electrotactile system by Kajimoto et al [11] and the tongue-based electrical

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stimulation by Kaczmarek et al [4]. Both interfaces used sensory substitution principles. Finally, some game environments have experimented with electrical input to the skin, for purposes other than force-related events, such as pain [12].

In this paper, we will take a closer look at force-related events that can be triggered using electrical stimuli. These stimuli are envisioned to cause pseudo-haptic events by changing the users pose through voluntary, but not self-induced muscular movements. Using NMES-based methods, wearable interfaces can be built that surpass limitations with body or ground-referenced devices, such as cost and immobility. By ways of an initial user test, first experiences have been made with electronically triggered muscle events. These events will be discussed by illuminating the physiological background, deducing useful factors to build up NMES-based haptic interfaces.

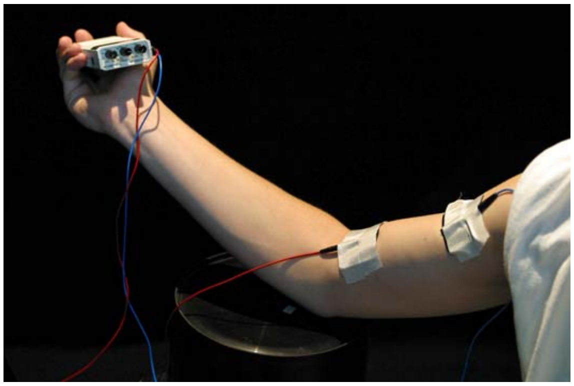

Figure 1: Neuromuscular electrical stimulation

2. EXPERIMENT SETUP

Due to the novelty of the method, an initial user test was prepared to create a basic understanding of the effects of neuroelectrical muscular stimulation. Within this test, muscular behavior (contractions) and possible side effects such as pain were observed, next to the user's attitude to this rather unconventional kind of feedback. The muscular contractions were caused by surface electrodes attached to either the biceps (forearm) or the brachioradialis (lower arm). The experiment made use of a non-immersive setup, resembling the setup proposed by MadCatz as game-like setup for games involving force feedback. The Mad Catz setup, though, solely triggered the brachioradialis, whereas (as stated before) we also triggered the biceps.

A basic 3D environment was used (Quake3), running on a laptop with a 14" screen. Subjects interacted via standard input devices, a mouse and keyboard, to control the game. The used electrodes were connected via cable with a TENS device (9V), a Schwa-medico SM2. Seven subjects (six male and one female user) participated at free will in this test, being informed on the possible health issues of using the system. The subjects had widely varying anthropometric characteristics. All users had at least intermediate experience with the game being played.

3. EVALUATION AND RESULTS

Following the identification of the users' background, the evaluation consisted of three stages. In the first stage of the experiments, the TENS was used to identify at which stimulation level the user would obtain feedback (muscle contraction) without causing pain, thus calibrating the device for each user. Using contact fluid, the electrodes were placed at either the biceps or brachioradialis muscle endings, and not moved until the end of the experiment. The TENS device was put on a low pulse rate (3 - 5 Hz, biphasic). A range of short and longer (up to 3 seconds) pulses was provided to the muscles in order to come to an appropriate stimulation level. The resulting maximum intensity in continuous mode turned out between 10 - 15 mA. Short shocks could be provided at up to 25 mA. The maximum stimulation level differed between users and was clearly dependant on the muscle and fat level and thickness of the arm: thicker skin and muscle tissues resulted in higher stimulation levels.

Biceps stimulation (four users) could be clearly noticed at two users. For the other two users a calibrated stimulation level was used at which contraction was minimal. The reaction of the muscles when placed at the brachioradialis (three users) could be better observed. With one user, a clear spasm in one of the fingers could be seen, probably caused by the triggering of an alternative muscle as intended. As a result, some changes in the biomechanical configuration (pose) of the arm and fingers were triggered and could be observed. The levels of input (up to 25 mA) were not expressed as being painful. Users expressed slight discomfort or some excitement and never seemed to loose grip on the input device, as was previously stated in informal statements on the usage of the Mad Catz Bioforce.

The second phase of the test focused at establishing small muscle contractions during game play. Whenever the user would get shot, a short but intensive stimulus (when hurt by explosive weapons) or continuous but lower intensive stimulus (when hit by a gun) would be given to the user. Users played a single round, during about 10 to 15 minutes. The TENS device was triggered manually, which resulted in a small delay of feedback. Only one user reported negatively on this delay. Due to the observation angle, the observer could observe both the game play and the muscle contractions without having to switch focal direction, and therefore attention, between the two. Hence, the observer could get a clear impression of both.

As within the first phase, muscle contractions could be clearly noticed with most users, especially when stimulation would be provided in continuous mode. When the biceps was triggered, the change of pose (noticeable in the change of the elbow arc) was at a maximum around 10 degrees, but regularly just a couple of degrees. During stimulation of the brachioradialis, contractions mostly lead to a change in the pose of the lower arm and hand. Contraction was not always completely continuous. A higher pulse rate could improve contraction by not allowing the muscle to relax, but could decrease user comfort (also see section 4). After the second phase, the users were questioned about their experience, using a questionnaire with a 5 point Likert scale.

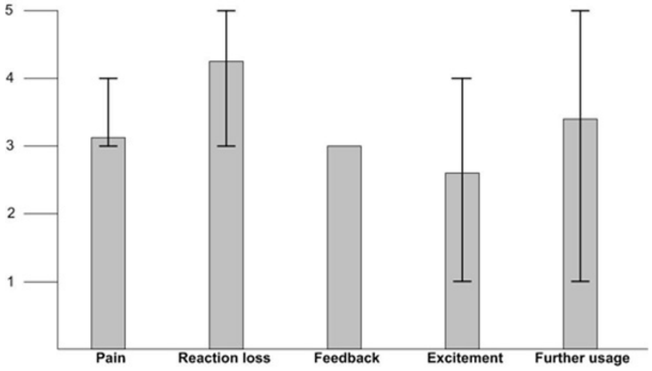

Figure 2: Evaluation results

The results are visualized in figure 2 (higher scores are better). The stimulation did not result in painful reactions – all users expressed that the feedback was at most uncomfortable (avg. 3.14, stdev 0.37). This result confirmed the calibration results and the observations during game play. The users stated they had no up till limited reaction loss (avg. 4.29, stdev 0.95). One user uttered that the stimulation was "irritating", when stimulation was provided in continuous mode for a considerable amount of time (5-10 seconds). In all cases, the electro stimulation was noticed as "somehow noticeable feedback" (avg. 3.00, stdev 0). Five of seven users found the stimulation to be funny or interesting; one user was even pretty excited. Two users did not find the stimulation exciting at all (note 1), which resulted in a diverse reflection (avg. 2.57, stdev 1.13).

Finally, the reactions on usefulness varied widely (avg. 3.42, stdev 1.86). Three users reacted extremely positive and stated a "definitive" further usage, also outside the games area. Two users reacted negatively (the same users as reacted negatively on excitement) on the feedback and certainly did not recommend usage outside entertainment purposes. These users also had most problems with user comfort: they reacted negatively to the kind of feedback being provided, being body-inflicting simulation that can irritate under circumstances (especially when not calibrated well enough). Finally, as expressed in direct discussion, none of the users had any problem relating the feedback to the game play. The "shock"- like feedback could clearly be connected by the actual event of getting hit.

4. DISCUSSION AND ROADMAP

The evaluation showed various issues that relate to potential, but also the problems of using neuromuscular electrical stimulation for pseudo-haptic feedback. Theoretically, neuroelectrical muscle stimulation can produce muscle contractions that can lead to the same kinds of movements as performed voluntarily using self-induced muscular activities. It is to be expected that stimulating solely the arm will not provide the full spectrum of movements such as afforded by methods like an exoskeleton, simply because some movements of the arm are also triggered by the shoulder, hence also using muscles at the back of a user.

This contraction is hard to control: one needs to trigger specific muscles to the right extend in order to create the wished change in the biomechanical configuration (pose) of the user. Furthermore, there may be a conflict between movements caused by electro stimulation and the body-internal voluntary signals that may level out muscle activity, depending on the thresholds of the potentials triggering the muscles. Thus it may well be that the voluntary control rules out some kinds of feedback, or poses distinct parameter changes in the NMES-based control, like the increase of intensity to overcome a specific potential threshold. There are no experiments known to the authors that deal with these problems.

Model of muscular behavior

The usage of NMES-based feedback is centered on the creation of a precise model of muscular behavior under effect of electrical stimulation. This model should show how the biomechanical configuration in the arm reacts to different electrical impulses to create directional feedback. The model needs to integrate effects of conditioning of the muscles, since stimulation effects will change over time [5]. Neuromuscular electrical stimulation applies low frequency, higher intensity pulses. These pulses, which are mostly biphasic, trigger the alpha motor nerves, which excite the muscles. This stimulation leads to a non self-induced contraction of a muscle. The higher the intensity of the stimulus, the more muscle fibers will be excited, leading to stronger contraction (twitch). A twitch can have different contraction speeds (explosivity). The duration of the contraction depends on the frequency of the impulse. When the frequency is high enough, the muscle will not have time to relax, thereby continuously staying contracted.

The model depends on the effects of stimulation resulting in both isometric and isotonic muscle contraction. Isometric muscle contraction leads to a tension in a muscle, without changing the length of the muscle, whereas during isotonic muscle contraction, the muscle does shorten. Muscles can be classified in four different functional groups [13]: prime movers, antagonists, synergists and fixators. The different muscles play an important role in the lever system which characterizes the bone-muscle relationship. This mechanical system defines the force or effort to balance a load, moving on a fixed point, the fulcrum. Most movements in the human body function according to a lever system. Excitation of a motor neuron by the nervous system produces exactly the same result as when provided through electrical stimulation – but now, the brain and spinal chord are not involved in the muscle activity.

Calibration methods

In order to stimulate the muscles to the right extend, and to ensure a high level of user comfort, there is a strong need for exact calibration methods. One of the problems noticed during the experiment is the trade-off between high intensity stimulation resulting in noticeable pose changes, and user comfort. Different effects of similar stimulation, caused by the different anthropometric variables such as arm tissue thickness or the level of skin hydration could be noticed.

For calibration, it is most likely needed to create an exact stimulation – biomechanical change model by tracking the user's arm via an exoskeleton or bend sensor(s).

Information from these sensors can also be useful for real-time controlling and adaptation of stimulation, thereby also take care of conditioning of the muscles.

Triggering of skin receptors

Another issue which should be dealt with is the triggering of skin receptors. During the experiment we had the impression that not only the muscle endings, but also specific cutaneous or subcutaneous receptors were stimulated. The triggering of these receptors might also have caused the feelings of pain or "buzzing", which were sometimes noticed by the users. The triggering of skin receptors can go into two directions: either avoiding the receptors to be triggered to prevent unwanted side effects, or to deliberately trigger the receptors to create specific tactile sensations.

Electrotactile stimulation can focus at one or multiple of the six available receptors that can be found in either glabrous or hairy skin. The receptors have different receptive fields (1-1000 mm^2) and frequency ranges (0.4 – 800 Hz), producing diverse sensory correlations. The receptors can roughly be classified according to the speed of adaptation to a step change in applied pressure to the skin [4]. There are fast adapting broad receptive-field receptors like the Pacinian corpuscle producing vibration tickle sensations, up to slowly adapting, small field receptors such as the Merkel's cells, handling pressure sensations. Within the body, the fingertips are by far the most sensitive, having a high spatial resolution. Not surprisingly, most haptic interfaces focusing at electrotactile feedback stimulate the fingers. Electrotactile stimulation and perception is rather difficult and does not necessarily lead to unanimous results. Depending on the stimulus characteristics (intensity, waveform) electrode size and material, and skin characteristics like thickness and hydration, perception may range from tickling, buzzing, beating, pressure, up to pain. Thus, a model of electrotactile stimulation should be carefully coupled to the model of muscular stimulation, thereby taking care of anthropometric variables.

Wearable hardware setup

A final issue that should be regarded is the actual hardware setup of the system, which would make use of a suitable automatic triggering mechanism to stimulate the muscles. As can be concluded from this article, neuroelectrical stimulation is well suited for lightweight installations, since there is no dependency on large body or ground-referenced devices. Hence, a wearable and thereby ergonomic and easily installable system could be developed. The problem is to deal with anthropometric variables: there is no one size fits all solution, since electrode placement most likely differs between users. Electrodes sewn in cloth-like constructions show good results, but more progress needs to be made [3].

5. CONCLUSION

Within this article, we presented a novel way for providing pseudo-haptic feedback by using neuromuscular electrical stimulation methods. We presented an initial user study, and an extensive physiological discussion addressing specific problems, which will hopefully lead to further investigations. We believe NMES-based feedback has great potential and could be highly interesting for wearable haptic solutions.

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