Flex your muscles: EMG-based serious game controls

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Abstract. In recent years, non-traditional input devices for digital games and applications such as wearable sensors have become increasingly available and affordable. Electromyography (EMG) promises some unique advantages over traditional input devices such as keyboards or gamepads by collecting input data directly at a person's muscle. As long as the corresponding muscle is intact, EMG can be used even when physical movement is not possible, for example when a person is injured or has an amputated limb. It also allows for unique wearable positioning on the body, potentially allowing for a larger freedom of movement.
In this paper, we examine whether an EMG-based input device is feasible to control an in-game character in a digital game. In order to do so, we first assess different EMG-related technologies and available EMG devices. Based on this assessment, we develop an EMG-based input device that can be connected to a computer. We develop a side scrolling game which can be connected to the EMG-based input device and allows for the player to switch between keyboard- and EMG-based controls. Lastly, we evaluate our developed system empirically and discuss the feasibility of EMG-based game controllers based on observed practical and theoretical limitations of the technology.

Keywords: Human-Computer Interaction · Health Games · Electromyography

1 Introduction

Typical input devices for games and other digital applications rely on directly capturing a person's movements, be it through a keyboard's buttons, a mouse's optical sensor or a game pad's joystick. In some cases, however, these methods can be impractical or even unusable, e.g. when the person's hand is in a cast because of an injury. Muscle-based controllers in general and Electromyography (EMG) in particular promise to be utilizable as an input device in these scenarios. Since EMG measures the resulting difference in current occurring whenever a muscle is activated, it can be utilized even when the intended movement cannot be carried out or measured. In addition to allowing people with physical limitations to interact with a game or an application, an EMG-based input device could also collect relevant medical data in a health game. This data could be used to adapt the game's difficulty in real time, or later be analyzed by a patient's physician in order to get more detailed information on the patient's health. Furthermore, an EMG-based input device can be utilized without obstructing a person's hands or other limbs, letting them interact with other objects instead.

In this paper, we examine the feasibility of using EMG as an input device for digital games, focusing on the usability of such a system at the player's home, i.e. without requiring a stationary setup or the oversight of a specialist. We first assess different technologies and hardware devices that can potentially be used in such a scenario. We present a prototypical EMG input device and a corresponding game which can be entirely controlled through the EMG input device. Lastly, we present and discuss our findings with respect to the usability of such an EMG input device in a practical scenario.

2 Background & Related Work

In this chapter we look at the background and the functioning of EMG and the new field of Mechanomyography (MMG) as an alternative to EMG. We also show related work where EMG devices are used to control applications and serious games. Finally, we introduce and compare a selection of applicable EMG devices.

2.1 Electromyography

EMG is used for measuring myoelectric signals. These are electrical signals that are generated during muscular activity of the skeletal muscles, which are responsible for voluntary, active body movements [17]. The signals can be measured by two different kinds of electrodes: Non-invasive/surface EMG-electrodes (sEMG), which can be placed on the skin, or invasive/intramuscular EMG-electrodes, which can be placed directly in the muscle. These sensors can be used to check whether a muscle is active, whether a muscle is tiring, how active a muscle is, in which movements a muscle is active and also the force exerted by a muscle [8].

Muscle activity causes potential changes at the muscle membrane. With surface EMG this signal is not measured directly on the muscle but is transmitted from the surrounding tissue to the skin and measured there. Thus the measurement depends on the conductivity of the tissue, which varies due to body fat and the condition of the skin. Signals from other muscles, including the heart, can also influence the measurement [17]. Accurate placement of the sensors is therefore essential, ideally near the muscle to be measured on shaved and disinfected skin. The use of an electrolyte gel to increase conductivity is not uncommon, so is the use of a reference electrode on a non-active limb [8, 18].

The surface EMG can be used with different types of electrodes [17]:

Monopolar electrodes When measuring with only one electrode, the direct process of the potential change of the observed muscle is measured. Interferences therefore have a direct effect on the signal, which is the reason why this method is rarely used [17].

Bipolar electrodes When measuring with two electrodes, both electrodes measure the same muscle. Since the potential change of the muscle is wavelike, it reaches the two electrodes at different times. A difference can now be calculated from the measured signals. This difference is less susceptible to interference than in a monopolar measurement, because the interference affects the electrodes in equal parts and is eliminated by the difference calculation [17].

Electrode Array An electrode array is used when larger areas of the skin are to be covered and thus several different muscles are to be measured simultaneously. It consists of several electrodes in series or as a matrix. The latter allows to bypass an exact positioning of individual electrodes. The measurements of the electrodes can be used separately or in sum - as in the bipolar measurement [15].

EMG is mainly used in the field of medicine and diagnostics, but also in the field of sports science [8]. Another area of application which is becoming more and more important is the field of Human-Computer-Interface (HCI) [18].

2.2 Mechanomyography

MMG is an alternative method of measuring muscle activity. Compared to EMG it measures the physical changes of the muscles and not the electrical signals which are emitted during muscle contraction [16]. Physical changes of skeletal muscles can lead to measurable acceleration, vibration and acoustics. MMG can therefor subdivided into three different approaches: Acceleromyography, vibromyography and phonomyography [6].

Talib et al. [16] analyzed various studies on MMG and were able to divide the used sensors into five categories: Accelerometers, microphones, piezoelectric sensors, displacement sensors and composite sensors.

MMG offers the advantage of a high signal-to-noise ratio combined with low sensitivity in sensor placement. It also has easy handling of setup up with the reliability of data [3].

A major disadvantage of MMG is that the technology is still in its beginnings and relatively unresearched. Therefore, there are no ready-to-use sensors to purchase at the moment [16].

2.3 Muscle controlled application

As mentioned in the introduction, EMG offers two major advantages when used as an input device:

Firstly, EMG can be used to detect muscle activity without the need of movement. This may happen when the corresponding limb is restricted in movement,

but also when it is completely absent, for example during an amputation. EMG can then be used to offer the patient an opportunity for interaction and is therefore also used in prostheses [4, 14]. Prahm et al. [14] describe a concept of using (serious) games to permanently motivate patients with prostheses to train their muscle coordination on a playful way and thus to better accept the prosthesis. The authors used three different kinds of games for their study: a racing game, a rhythm-based game and a dexterity game. The games were controlled by two EMG-electrodes, which allowed movement by one Degree of Freedom (DoF).
There are also other play-oriented approaches for people with prostheses, such as an adaptation of the commercial video game Guitar Hero© III, which is controlled by six or more EMG electrodes and does not require the use of any keys [4]. Oppenheim et al. [11] developed WiiEMG, a EMG-based Wii™ controller, to promote the rehabilitation of the patients' motor skills.

The second advantage of EMG is, that muscle activity of limbs can be measured without restricting the limbs themselves. For example, the movement of a hand can be measured while interacting with objects or gesticulating freely. Wu et al. [19] use four EMG-electrodes in combination with one Inertial Measurement Unit (IMU) to recognize signs. Their approach recognizes 80 commonly used ASL signs with an accuracy of up to 96.16%.
The EMG wristband *Myo* from the company *Thalmic Labs* for example also supports the control of drones and robots via gestures captured with the wristband [1].

Another example is described by Pai et al. [12], who present a system that uses eye tracking for cursor movement and EMG on a user's forearm to make selections in Virtual Reality (VR).

2.4 EMG-devices

The design of a muscle-based gesture controller should be preceeded by a comprehensive literally hardware analysis. Since a muscle-controlled game is to be developed, the following aspects should be considered:

- Ease of use (weight, size, wired / wireless, etc.)
- Real-time capability
- Usability for the scenario of a muscle-controlled game
- Sufficient number of channels to track muscle activity of up to five fingers and arm
- Technical key figures like Sampling Rate, Bandwidth/filter and gain
- Problems and ambiguities that could arise when using the setup

The following is an overview of EMG sensors available on the market.

Grove-EMG-Detector[1]: The *Grove-EMG detector* is a basic EMG-sensor which allows 3 disposable skin surface electrodes to be connected simultaneously via wire. The EMG signal is amplified and filtered, but further details

[1] https://wiki.seeedstudio.com/Grove-EMG_Detector/ - Last visited on 03.07.2020

are not known. The sensor is compatible with the *Grove* system - a plug-in system to make cable connections between different components easier. For *Arduino Uno* there is a *Grove* extension, the *Grove Shield*. However, it has only 4 analog connectors and can therefore only be equipped with up to 4 EMG-sensors. For the *Arduino Mega* there is also a larger version, the *Grove Mega-Shield*, with 8 analog connectors.

The producer explicitly states that the sensor is not suitable for medical purposes.

The system is for example used by Krivosheev et al. [9] for recognizing gestures and by Borisov et al. [5] for controlling a prosthesic hand.

MyoWare Muscle Sensor[2]: The *MyoWare* muscle sensor is a simple EMG sensor like the *Grove - EMG detector*. In contrast to this one, it can not only be used with external skin surface electrodes, but can also be attached directly to the body. The output signal can be either a rectified and integrated analog signal or the analog RAW data. The gain is adjustable.

Medical devices are mentioned as an application example, but a corresponding certificate is missing.

The system is for example used by Latif et al. [10] for designing a muscle and flex sensor controlled robotic hand for disabled persons and by Ahmed et al. [2] for building a EMG-driven nobility assistance robot for disabled persons.

Thalmic Myo[3]: The *Thalmic Myo* is a All-in-one solution in the form of a EMG wristband. In addition to medical stainless steel EMG sensors, it consists of a 9-DoF-IMU and an integrated ARM Cortex M4 processor. It can transmit data wirelessly via integrated Bluetooth.The possibility of haptic feedback and an integrated lithium-ion battery complement the system. It has a sampling rate of 200 Hz (sEMG) at 8 bit and a notch filter at 50 Hz.

Pizzolato et al. [13] compare the *Talmic Myo* in their paper with 5 other EMG systems (including the *Cometa Waves + Dormo* and *Delsys Trigno* presented here) and used the approach of using two wristbands simultaneously, among other things. These were placed slightly shifted to each other on the same arm.

Using two wristbands could increase the accuracy by about 25% compared to one wristband and is comparable to the *Delsys Trigno*, which gave the most accurate results but also cost 30 times more than two *Thalmic Myos*.

Cometa miniWave[4]: The *Cometa miniWave* is a small, compact, lightweight and wireless All-in-one solution. It has a resolution of 76 nV/bit at a sampling rate of 2 kHz at 16 bit and a bandwidth with HPF at 10 Hz and LPF at 1kHz. The gain is 1,000.

One unit has two EMG electrodes and a 3-DoF accelerometer and can measure one muscle. The battery life is 10 hours and can be recharged by inductive charging.

[2] https://www.sparkfun.com/products/13723 - Last visited on 03.07.2020

[3] https://www.vdc-fellbach.de/leistungen/technikbewertung-var/thalmic-labs-myo-gesture-control-armband/ - Last visited on 03.07.2020

[4] https://www.cometasystems.com/products/mini-wave - Last visited on 03.07.2020

Delsys Trigno Wireless System[5]**:** The *Delsys Trigno Wireless System* consists of several sensors that measure acceleration and orientation in addition to EMG signals. Each sensor can be attached directly to the body and transmits the data wirelessly. The power supply is provided by a built-in rechargeable battery. The resolution is 168 nV/bit with a sampling rate of 2 kHz at 16 bit and a bandwidth of 20-450 Hz / 10-850 Hz. The gain is 909 ± 5. Pizzolato et al. [13] compare in their work 6 different EMG-systems where the *Delsys Trigno*) could provide the most accurate results.

Bagnoli EMG System[6]**:** This setup is a classic wired system with the emphasis on easy handling. It has 16 channels, where the amplification can be adjusted individually. It has a bandwidth of $20 - 450Hz \pm 10$ at a gain of 100/1000/10000. The system manages and conditions the signals and provides feedback if signals are cut off due to excessive gain. The output is analog, but the system can be connected directly to a PC with a special card.
The system is approved as a medical device and is for example used by Khushaba et al. [7] for improving control of prosthetic fingers.

The advantages and disadvantages of these EMG systems can also be found in Table 1.

3 Approach

In the following, we will present the prototype we developed to assess the feasibility of an EMG input device for a digital game to be played at home. Our prototype consists of a wearable surface EMG system which records EMG signals of two different skeletal arm muscles as well as a game which processes the recorded data in real time in order to control the player's character.

3.1 EMG system

Whereas intramuscular EMG has significant advantages over surface EMG in many areas such as signal to noise ratio or number of applicable muscles, it is also highly invasive and cannot be safely used by an untrained person at home. With one of our requirements being the usability for a player at home, we therefore use a less invasive surface EMG system for our prototypical EMG controller.

Our EMG controller consists of a MyoWare muscle sensor to record muscle activity and an Arduino Uno which acts as an analog-to-digital converter before sending the converted data to the computer running the game using a USB connection. The USB connection doubles up as a power source for the system. Alternatively, a Bluetooth module and a battery holder can be added to

[5] https://www.delsys.com/trigno/research/ - Last visited on 03.07.2020
[6] https://www.delsys.com/bagnoli/ - Last visited on 03.07.2020

Table 1. Advantages and disadvantages of several examined EMG systems

System	Type	Advantages	Disadvantages
Grove-EMG-Detector	Sensor	– Easy data exchange and power supply through Grove system – Data easily accessible	– Wired – Only 4/8 channels – Not suitable for medical purposes
MyoWare Muscle Sensor	Sensor	– Easy to assemble – Raw and Integrated Data – Easy to scale up – Easily expandable for different purposes	– Wired – Only 4/8 channels – Not suitable for medical purposes
Thalmic Myo	All-in-one solution (wristband)	– Easy to wear bracelet – Does not require any preparation on the skin	– Fixed electrode spacing – No longer available
Cometa mini-Wave + Dormo	All-in-one solution	– Small, light and handy – Wireless	– Requires as many units as muscles to be measured – Preparation on the skin necessary for the electrodes
Delsys Trigno Wireless	All-in-one solution	– Wireless – Suitable for sports applications – Precise measurement results	– Expenditure for real-time applications must be clarified – Larger sensors, unsuitable for narrow places (hand) – Scalability must be clarified
Bagnoli EMG System	All-in-one solution	– Simple setup – Usable for gesture recognition – Direct access to (analog) data – Certified for medical purposes	– Cabled – Real-time data only with additional hardware – 16 channels, not scalable

enable wireless functionality at the cost of additional weight. Whereas our prototype utilizes a relatively large Arduino Uno as a microcontroller board, smaller boards such as the Arduino Nano or custom microcontroller boards can be used in practice to reduce the impact on player comfort. Compared to complete solutions such as the Thalmic Myo, our approach has the advantage of being easily adaptable and extensible to a given use case while also being more affordable in practice. For example, a more complex game might require additional EMG sensors or a disabled player might require sensors in different positions to be able to use the EMG controller.

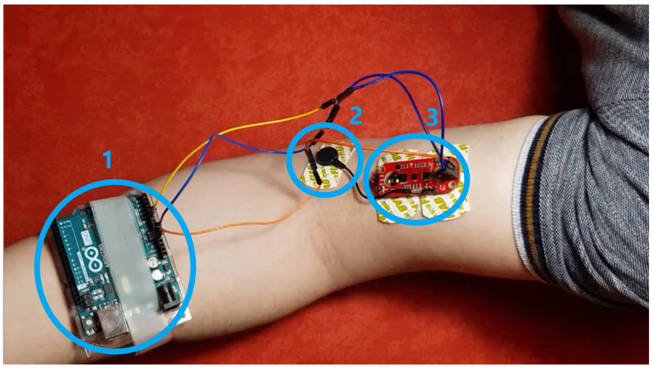

Fig. 1. Applied EMG system consisting of an Arduino Uno (1), a reference electrode (2) and a MyoWare muscle sensor applied to the Biceps brachii (3)

Figure 1 shows our EMG controller when applied to the player's arm. For our system, we apply three electrodes in total; two electrodes to measure the activity of the Biceps brachii and one electrode as a reference electrode. The Biceps brachii is one of the primary muscles involved in the flexion of the forearm at the elbow. By measuring its muscle activity, we can therefore determine whether the player is currently attempting to flex their forearm. The reference electrode is placed at an arbitrary part of the forearm without muscle activity, e.g. a bony part of the elbow. The muscle activity for the Biceps brachii is then calculated as the difference between the electrical activity measured at the Biceps brachii and the electrical activity measured at the reference electrode.

Figure 2 shows how the EMG controller can be expanded by additional muscle sensors. The additional muscle sensor is applied to the Flexor carpi ulnaris at the player's forearm. The Flexor carpi ulnaris is one of the primary muscles involved in the flexion of the wrist. By measuring its muscle activity, we can therefore also determine whether the player is currently attempting to flex their wrist. Since each MyoWare muscle sensor uses their own reference electrode, an additional reference electrode is placed at the back of the elbow (not visible in figure 2.

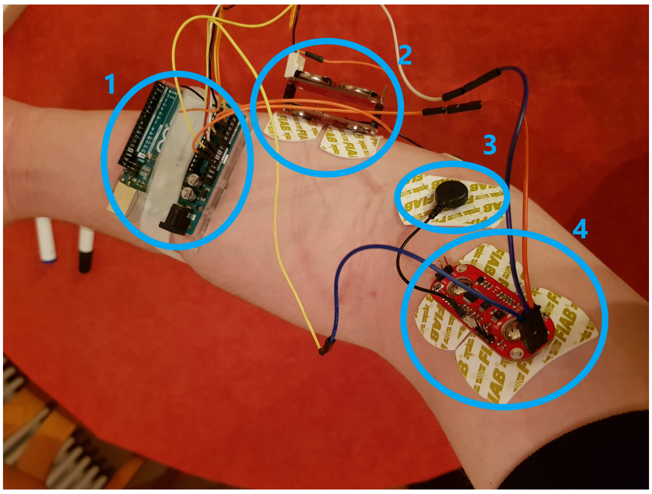

Fig. 2. Applied EMG system consisting of an Arduino Uno (1), a MyoWare muscle sensor applied to the Flexor carpi ulnaris (2), a reference electrode (3) and a MyoWare muscle sensor applied to the Biceps brachii (4)

The Biceps brachii and the Flexor carpi ulnaris were chosen as appropriate muscles to measure muscle activity based on their distinct function and high accessibility via surface EMG as a result of their respective size and position. A large number of muscles, particularly in the forearm, are either concealed by other muscles or too small for accurate surface EMG measurement and are therefore not suited for a surface EMG approach. Even though our setup can be easily expanded by additional muscle sensors, this puts a hard limit on the number of muscles that can be measured by this approach in a given area of the body.

3.2 Software

The microcontroller on the Arduino Uno converts the rectified and integrated EMG signal produced by the MyoWare muscle sensors into a digital signal and forwards it to the connected computer, appending a unique identifier for each source muscle sensor to each data package. On the computer, an API stores all received muscle sensor data for a fixed time span of one second before discarding it. A game can utilize this API to access the latest sensor data values, rescaled to a desired value range, at any given point in time.

In order to assess whether our system can be used as an effective input device for a game, we designed a simple side scrolling game in Unity[7] in which the player controls a space ship (see figure 3. The goal of the game is to avoid

[7] https://unity.com/ - Last visited on 04.07.2020

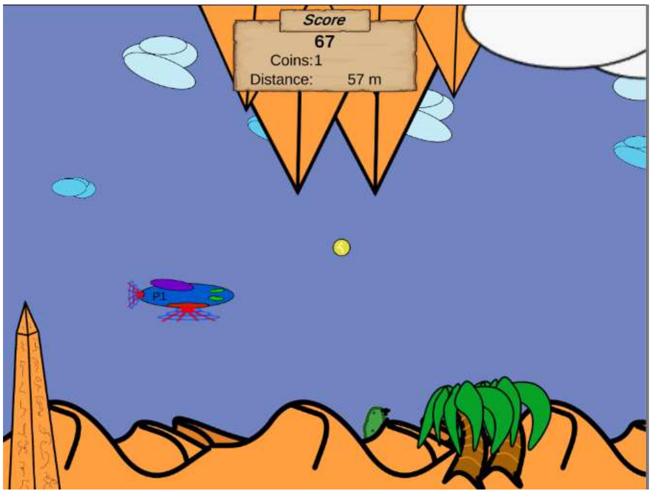

Fig. 3. The developed side scrolling game with a controllable space ship

touching any obstacles for as long as possible while collecting as many coins as possible on the way. Without the EMG-based input device, one key on the keyboard can be used to move the space ship upwards whereas another key can be used to shoot. The space ship continuously moves rightwards and slowly moves downwards if no upwards command is input. With the EMG-based input device, two different modes exist: If the basic setup with a single muscle sensor is used, that muscle is used to move the space ship upwards and the ship automatically shoots continuously. The space ship can therefore be moved upwards by tensing the Biceps brachii, e.g. by flexing the forearm, and moved downwards by releasing the tension. If the setup with two muscle sensors is used, the second muscle sensor is used to shoot. A player can thus shoot by tensing the Flexor carpi ulnaris, e.g. by flexing their wrist.

Before starting the game, the player has to choose whether to use an EMG-based input device and, if so, whether a second muscle sensor is used to shoot. If an EMG-based input device is selected, all muscle sensors are then calibrated as shown in 4. For each input type (*thrust* or *shoot*), the player selects the according muscle sensor by its device ID. For each muscle sensor, the player is then asked to relax and then tense the respective muscle for five seconds each. The recorded values are then used to determine a minimum and a maximum muscle sensor value for the given muscle sensor in order to translate sensor values into game inputs. During gameplay, the game periodically polls the API for the latest sensor data value for each connected muscle sensor. The sensor value is then converted into an input value using the minimum and maximum values determined during calibration and used similar to how e.g. a joystick's angle would be used.

Fig. 4. EMG calibration process

4 Discussion

We could not conduct an extensive user study for our developed system because of the aggravated regulations following the outbreak of COVID-19. Instead, we rely on the empirical data collected when developing and testing the system in order to assess whether our system in particular and EMG-based systems in general are applicable as input devices for digital games.

With correctly applied electrodes, we found the EMG-based input device to be a usable input device after a settling-in period of typically less than a minute, i.e. players were able to control the space ship to a comparable degree to the key-based input. An input delay was noticeable but not large enough to be disruptive for our game. We expect this to be a problem for faster and more reaction-based games though and thus would not recommend an EMG-based input device for such games.

Despite only using a maximum of two muscle sensors, we found the process of applying the single-use adhesive electrodes to be unpleasant and relatively time-consuming compared to traditional input devices, especially since they require very clean and hairless skin to achieve good contact. Furthermore, we found the system to be susceptible to artefacts when connecting additional wired electrodes to the muscle sensors, particularly when their respective cables moved. Whereas conductive fabric electrodes can be used to alleviate these issues, we expect them to provide significantly more noisy data in general since they do not ensure as good skin contact as adhesive electrodes.

Lastly, our approach comes with significant limitations, most of which apply to surface EMG in general. One such limitation is the noise related to surface EMG when compared to intramuscular EMG, preventing precise movements from being accurately captured. Furthermore, surface EMG can only be used for muscles close to the skin surface which are large enough to provide a significant electrical signal and not covered by other muscles. It can therefore not be used to capture all movements that traditional input devices can capture.

Overall, we consider a surface EMG-based controller to be a feasible input device for digital games, albeit only for very specific scenarios and types of games where their distinct advantages fully apply, such as when a player is physically impaired or EMG data is also used for medical purposes. We don't recommend using it in games where quick reactions or precise movements are mandatory.

5 Conclusion

EMG offers many interesting applications in the fields of medicine, sports and, as shown in this paper, also in the field of HCI. We developed an EMG-based input device as well as an accompanying side scrolling game which can be played entirely by muscle activation. The game supports two different arm movements for which muscle activity between tense and relaxed is translated into game input, allowing for the game to be fully controlled with just muscle activation.

Whereas the EMG-based input device works well for the simple side scrolling game we developed, we could identify a number of restrictions that apply when utilizing such an input device for other games and scenarios. An EMG-based input device is therefore not suited for games that require quick reflexes or precise movements and cannot be used for movements with inaccessible muscle regions.

In future work it is worth looking at whether additional muscle sensors can be utilized to detect finer movements such as finger movements. In order to achieve more precise results, an EMG-based approach could also be augmented by additional sensors such as IMUs. Furthermore, it is worth looking into the accuracy that can be achieved by EMG-based systems for different movements and how it compares to traditional input devices.

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