IMPACT OF TANGIBLE AUGMENTED REALITY ON ELECTROMYOGRAPHY OUTPUT

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Presented to
The Academic Faculty

by

Kelly Choe Fischer

In Partial Fulfillment
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IMPACT OF TANGIBLE AUGMENTED REALITY ON ELECTROMYOGRAPHY OUTPUT

Approved by:

Dr. Young Mi Choi, Advisor
School of Industrial Design
Georgia Institute of Technology

Prof. Leila Aflatoony
School of Industrial Design
Georgia Institute of Technology

Prof. Timothy Purdy
School of Industrial Design
Georgia Institute of Technology

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LIST OF SYMBOLS AND ABBREVIATIONS

\( i \) Electromyography Segment Increment

\( N \) Length of Electromyography Segment

\( \mu V \) Microvolts

\% Percentage

\( \sum \) Summation

\( x_i \) Value of Electromyography Amplitude

AAC Average Amplitude Change

AR Augmented Reality

CSV Comma Separated Value

DASDV Difference Absolute Standard Deviation

EMG Electromyography

Hz Hertz

iEMG Integrated Electromyography

imEMG Intramuscular Electromyography

LED Light Emitting Diode

MAV Mean Absolute Value

MAV1 Modified Mean Absolute Value 1

MAV2 Modified Mean Absolute Value 2

SSI Simple Square Integral

VAR Variance of Electromyography

RMS Root Mean Square

V V Order
LOG  Log Detector
sEMG  Surface Electromyography
TAR  Tangible Augmented Reality
VAR  Virtual Augmented Reality
WL  Waveform Length
SUMMARY

In recent years, surface electromyography signals have been used in pattern recognition and rehabilitation settings. There has been much exploration in the most effective methods for signal identification, collection, processing, and classification. A further step in the future application exists in the viability of carrying out these methods quickly and efficiently to produce real-time interpretations and haptic feedback of the EMG signals for prostheses and robotics. While it is not a new avenue to consider multi-sensory influence on muscular stress and activation, altering sensory input and the potential impact of augmented reality on the body is relatively untouched. Previous technological limitations with augmented reality have been overcome to produce systems of greater human-computer interaction and flexibility.

This study proposes incorporating electromyography sensors with tangible augmented reality during the completion of a series of low stress motion-based tasks to determine the potential impact on muscular activation by the users. Specifically, 3 tasks were completed by the users in a laboratory setting while equipped with an EMG armband and their subsequent signal output recorded for those tasks. The same tasks were then completed with the utilization of a simple tangible augmented reality system, and the ensuing signal outputs recorded once more. These signal outputs are gathered by an armband consisting of 8 surface electrodes which can record the EMG signals generated from the muscles in the forearm for each task performed by the user. The tangible augmented reality system incorporates a digital visual interaction with representative physical interactions of the tasks to best mimic the real-life tasks performed by users. Two
key signal classification features, integrated electromyography value and waveform length, were analyzed to determine what influence the TAR system had on EMG output. The changes in iEMG and WL values for the tasks after implementing the TAR system appear to reflect an increase in EMG and potentially muscular activation from the participants.
CHAPTER 1. INTRODUCTION

Electromyography is the detection and recording of electrical activity generated by muscle fibers. These elements of control in the human body are the motor units that make up neurons, their axons, and hundreds of muscle fibers supplied by the motor neurons (Brown, 2013). The size and properties of the motor units varies, along with conduction velocities of the axons, morphology of nerve muscle junctions, and the physiological properties of the muscle fibers (Brown, 2013). Augmented reality is an experience where the user’s interactions are enhanced through sensory modalities and often computer-generated input. The utilization of augmented reality for guiding user motions and the incorporation of sensors as an assessment tool are areas of growing application and interest (Chen, 2020 & Limbu, 2019).

1.1 Background

The application of electromyography has been used specifically in the medical and physical therapy fields as a technique for assessment, tracking, and implementing rehabilitation methods. Surface electromyography comes with the advantages of being easier to set up and incorporate with other devices as well as being non-intrusive. There exists discord between the current relationship of exercise recommendation in the realm of physical therapy and muscle strengthening with the extent to which these conscious efforts affect muscle activation over time (Kristof et al, 2019). Supplemental devices may also be incorporated to physical therapy and rehabilitation sessions, either with a professional trainer present or at home solely up to the patient’s use. These devices have ranged in
testing and application from game-based therapy, stimulator training, electromyography driven robotic devices, and neuromuscular electrical stimulation (Klein et al, 2018).

1.2 Research Goals

The goal of this study is to determine the impact of the change in visualization and interaction methods on muscle activation in the user while performing low stress motion-based tasks. Any findings will ideally enable future development for designing tangible augmented reality systems to consider changes in biomechanical stress and responses for users, in addition to the benefits or drawbacks that may come from using various types of AR to seek specific muscular activation. The objectives of this research are:

- Provide an overview of EMG and the current applications to identify open avenues of development for prosthetics or rehabilitation
- Identify techniques used in processing EMG signals and the benefits or drawbacks of these techniques for measurement
- Explore the current status and future potential of augmented reality and the considerations involved in producing a usable system
CHAPTER 2. LITERATURE REVIEW

2.1 Electromyography

There are numerous methods to detecting and assessing the activation of muscles in the body, such as:

- **Mechanomyography**: the measurement of muscle contraction based on the vibrations produced by muscle fibers upon contraction, a reflection of the mechanical counterpart of motor unit activity measured by electromyography (Talib et al., 2018).

- **Change of electrical impedance**: changes to global muscle resistivity when transitioning from a resting state to an active state due to blood flow (Silva et al., 2014). Pneumatic sensors:
  - Changes in air pressure of an air bladder contacting the muscle (Jung et al., 2015). Textile pressure sensors embedded in clothing (Zhou et al., 2016).

- **Optical properties**: detecting muscle contraction through LEDs and photodiodes by measuring backscattered light from muscle tissue (Bansal et al., 2014).

Electromyography signals are the electrical activity of a muscle’s motor units. To read the EMG signals from the user, surface electrodes are used. When the users move, electrical signals generated by the muscles can be recorded from the surface of the skin. This form of EMG is called surface electromyography (sEMG). sEMG is an alternative to embedding needle electrodes directly into the muscles which is called intramuscular
electromyography (imEMG). EMG signals are being utilized more and more in clinical/biomedical applications, prosthesis or rehabilitation devices, human-machine interactions, and more.

The incorporation of electromyography sensors in daily life often goes unnoticed or as an afterthought, especially as recent health trends and general activity awareness increase, driving the fitness tracking market particularly with wearables (Medical Devices & Surgical Technology Week, 2020). The accuracy of these wearables for real time fitness tracking is often questioned, though in general they come to provide comprehensive feedback of physical activity to users. Shifting position of the wearable, skin formation, blood flow, skin temperatures, tissue structure, and measuring site are just a few of the variables that can affect the readings provided by electromyography. Quality of EMG signal can also be affected by crosstalk with adjacent muscle activation and positioning of the electrodes (Esposito et al., 2018). Though it has been noted that the non-invasive electrodes can provide clearer signal and measurements when increased in size, and the signal-to-noise ratio increases when the electrode is smaller in size (Chowdhury et al., 2013). The compact nature of non-invasive electrodes for wearable technology is expected, as many consumers would show reluctance in purchasing a device that may impede daily activities or prove to be a distraction.

Electromyography use for physical therapy has displayed a multitude of outcomes, though many of which suggest favorable muscle activation with conscious correction (Kristof et al., 2019), new approaches to intramuscular electromyography decomposition, coherence of motor unit firing patterns from surface electromyography (Klein et al., 2018), and the exploration of the relationship between electroencephalogram and
electromyography signals in clinical rehabilitation settings (Li & Yang, 2019). There have been observed changes in upper limb electromyography activity after users followed a 14-day Wii-based Movement Therapy program in chronic stroke survivors (Hesam-Shariati et al., 2017) as well as higher motor outcomes in the joints and more effective reduction in muscle tone for subacute stroke survivors via neuromuscular electrical stimulation combined with robotic training over the course of 20 sessions in a month (Qian et al, 2017). The identification of muscular activation impairment is an area open to exploration, as the recording and analysis of peripheral or central electromyography combined with other signals can provide a means to assess these mechanisms (Jones & Kamper, 2018).

2.2 Signal Processing

The detection, processing, and classification analysis in electromyography can allow for standardized practices and precise evaluation of the findings (Chowdhury et al., 2013). The interference of noise from various sources can contaminate the readings, which can make the analysis and classification of the signals to be very difficult. Advanced methodologies such as wavelet transform, Hillbert spectrum (Andrade et al., 2008), independent component analysis, and empirical mode decomposition have been used by researchers for analyzing the electromyography signal appropriately. While it remains difficult to remove the noise completely, current electronics and differential amplification enable the measurement of EMG signals with low noise and high signal fidelity, which is high signal to background noise ratio. Filtering noise from recorded signals often utilizes low pass filters, which passes signals of a frequency lower than a determined cutoff but removes signals of a higher frequency, i.e., background noise. This is done to avoid signal
aliasing where different signals become indistinguishable from one another upon collection (Gerdle et al., 1999).

Pattern recognition and classification developments have provided improvement in the extraction of information from EMG signals particularly applied the degree of freedom of prosthetic control. Regarding pattern classification, feature extraction attempts to extract relevant and usable information from the EMG signals. Previous studies have shown that the determined feature sets, which maintain class separability, influence signal classification accuracy more so in the choice of feature set rather than the choice of classifier (Parker & Scott, 1986).

One study found that not only did data collected from subjects reflect similar classification accuracy between various classifiers provided with the same feature set, but also there was no significant difference in classification accuracy between intramuscular and surface measurement techniques in this case. Increasing the number of channels to improve classification accuracy has been observed, but the increase follows an exponential development rather than linear improvement. Further, when applying symmetrical channels there was no benefit in adding more than four channels and an observed decrease in accuracy when increasing from 8, 10, 12, or 14 channels to 15. With this, 97% classification accuracy could be achieved by choosing only 3 of the 15 measured sEMG channels (Hargrove, 2007).

Two prominent feature types for classification are time-domain and frequency-domain. Time-domain features do not require transformation and can be calculated based on raw EMG time series. Frequency or spectral domain features have mostly been used to
study muscle fatigue and motor unit recruitment analysis. Time domain features have been greatly used for their classification performances and the low computational complexity compared to those in frequency domain and time-scale domain sets. One study analyzed the classification accuracy of 37 different features, 26 time-domain and 11 frequency-domain. The redundancy of EMG features was evaluated and found that time-domain features could be grouped into four main method groups based on mathematical properties: energy and complexity information methods, frequency methods, prediction model methods, and time-dependence methods. Features of the energy and complexity information methods and the frequency methods were shown to have little difference from each other while having better performance than features in the prediction model methods and time-dependence methods in terms of discrimination and classification accuracy.

The energy and complexity group can be subsequently divided into two subclasses of features. Subclass 1, based on energy information, consists of nine features (see Table 1): iEMG, MAV, MAV1, MAV2, SSI, VAR, RMS, V, and LOG. Subclass 2, based on complexity information, consists of three features (see Table 2): WL, AAC, and DASDV. (Phinyomark, 2012). In the equations below $N$ is the length of the segment, $i$ is the segment increment, and $x_i$ is the value of the signal amplitude.
<table>
<thead>
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<th><strong>Table 1. Time-domain subclass 1 features</strong></th>
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<tr>
<td><strong>iEMG</strong></td>
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<tr>
<td>[ iEMG = \sum_{i=1}^{N}</td>
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<tr>
<td><strong>MAV</strong></td>
</tr>
<tr>
<td>[ MAV = \frac{1}{N} \sum_{i=1}^{N}</td>
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<tr>
<td><strong>MAV1</strong></td>
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</tbody>
</table>
| \[ MAV1 = \frac{1}{N} \sum_{i=1}^{N} w_i |x_i| ; w_i = \begin{cases} 
1, & \text{if } 0.25N \leq i \leq 0.75N \\
0.5, & \text{otherwise}
\end{cases} \] |
| **MAV2**                                   |
| \[ MAV2 = \frac{1}{N} \sum_{i=1}^{N} w_i |x_i| ; w_i = \begin{cases} 
1, & \text{if } 0.25N \leq i \leq 0.75N \\
4i/N, & \text{else if } i < 0.25N \\
4(i-N)/N, & \text{otherwise}
\end{cases} \] |
| **SSI**                                    |
| \[ SSI = \sum_{i=1}^{N} x_i^2 \] |
| **VAR**                                    |
| \[ VAR = \frac{1}{N-1} \sum_{i=1}^{N} x_i^2 \] |
| **RMS**                                    |
| \[ RMS = \sqrt{\frac{1}{N} \sum_{i=1}^{N} x_i^2} \] |
| **V**                                      |
| \[ V = \left( \frac{1}{N} \sum_{i=1}^{N} x_i^p \right)^{\frac{1}{p}} \] |
| **LOG**                                    |
| \[ LOG = e^{\frac{1}{N} \sum_{i=1}^{N} \log(|x_i|)} \] |
Table 2. Time-domain subclass 2 features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Formula</th>
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<tr>
<td>WL</td>
<td>$WL = \sum_{i=1}^{N}</td>
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<tr>
<td>AAC</td>
<td>$AAC = \frac{1}{N} \sum_{i=1}^{N-1}</td>
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<tr>
<td>DASDV</td>
<td>$DASDV = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_{i+1} - x_i)^2}$</td>
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2.3 Augmented Reality

Augmented Reality systems are being integrated to training methods and work simulations as supports for reducing performance errors while executing procedures, increasing memorability, and improving costs and time efficiency of training (Helin et al., 2018). The development of technology has removed many limitations for AR and allowed its development into a more favorable alternative to human-computer interaction due to its inclusion of intuitive interactions with higher levels of navigational flexibility, freedom, and three-dimensional interfaces (Cometti et al., 2018). There has been promise in the application of AR with maintenance and instruction (Re & Bordegoni, 2014), AR-based job aid (Anastossova et al., 2005), and AR-based assembly guidance (Ong et al., 2008). As these methods are often more cost effective than construction of a physical mockup, it is vital to ensure that conclusions drawn from virtual environment testing accurately emulates
the conclusions which would be drawn from a real environment (Hilt et al., 2021). Visual feedback from systems has been shown to act as cues for engagement of physical activity, as seen with one study with boxers. Initial recordings of average punches within a 30 second timeframe in the control group were significantly higher than those from the experimental group. The experimental group, with exposure to the recorded readings and data, saw an increase in an average of 35.7 punches, while in the control group the average increased by only 1.71 punches (Arnautu et al., 2021).

Usability of virtual environments has been described and measured by the assessment of three main features: simulation, display, and interaction fidelity (Alexander et al., 2005 & McMahan et al., 2012). There is often a lack of interaction in the testing of digital mock-ups of work environments and a virtual reality setup. With this limitation comes the issue of thorough investigation of the user's biomechanics and ergonomic assessment (Samani et al., 2015). With the addition of another feature, biomechanical fidelity, or biofidelity, the degree of similarity between motions, forces, and tasks in real environments and virtual environments. Indicators such as averaged muscle activation, average distance of motion trajectories, motion path length, and average maximum motion speed have displayed significant differences from testing real environment objects and virtual environment objects (Hilt et al., 2021). Producing a high biomechanical fidelity rate in AR and TAR systems would ensure that conclusions and results from user testing in these environments are consistent with projected real environment testing, activity, and risks (Pontonnier et al., 2014).

The effects of virtual reality tasks have been explored not only on mental engagement and fatigue but physical impact as well. Some studies have shown that long
exposure to VR and AR can incite cyber sickness with decreased reaction time with correlation to nausea and increased heart rate (Nalivaiko et al., 2015 & Kroes et al., 2017). Musculoskeletal loading and task performance during these interactions are significantly influenced even without the inclusion of tangible simulation of the virtually projected objects (Penumudi et al., 2020). The increase in discomfort from users in augmented environments resulting from excessive virtual targets and their locations acts as a warning for development of transverse dimensional reality systems. The measurement of biomechanical and physiological markers such as stomach activity, blinking, muscle activation, and breathing can be indicators of fatigue when using AR (Dennison et al., 2017). In addition, inattention to added stress from AR systems in users may result in negative effects on balance (Park et al., 2017), visual fatigue (Gamberini et al., 2015), and cognitive load (Baumeister et al., 2017). A major technological challenge with TAR is the limited computational resources, namely with tracking target objects accurately and timely while taking into consideration potential trade off with computational latency (system lag) and minimizing misregistration of targets (Bach et al., 2018).
CHAPTER 3. RESEARCH OVERVIEW

3.1 Aim and Objectives

- Collect EMG data from individuals while they conduct a series of motion-based tasks in real-life settings compared to the same tasks carried out with the incorporation of a TAR system
- Determine which signal features represent the EMG data best for analysis
- Identify any relationships in the EMG values from real-life tasks to TAR tasks

3.2 Participants

Basic information of the users was gathered through a pre-study questionnaire to record age, gender, race, and dominant arm. Eighteen participants (13 male; 5 female) ranging from the ages of 22 years and 28 years and an average age of 24.72 ± 1.27 years participated in the study (see Table 3). Participants were healthy and free of any motor limitations or injuries with their dominant arm. Users with serious injury or current disability that prevents full, uninhibited motion of the dominant arm and fine motor control of the dominant hand were not measured in this study to decrease unknown influences in EMG signal readings.
Table 3. Participant demographics

<table>
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<th>race</th>
<th>dominant arm</th>
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<td>Caucasian</td>
<td>R</td>
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<td>24</td>
<td>F</td>
<td>Asian/Caucasian</td>
<td>R</td>
</tr>
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<td>p3</td>
<td>25</td>
<td>M</td>
<td>African American</td>
<td>R</td>
</tr>
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<td>23</td>
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<td>Asian/Caucasian</td>
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<td>R</td>
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<td>R</td>
</tr>
<tr>
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<td>M</td>
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<td>R</td>
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</tr>
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<td>26</td>
<td>M</td>
<td>Caucasian*</td>
<td>L</td>
</tr>
<tr>
<td>p18</td>
<td>26</td>
<td>M</td>
<td>Caucasian*</td>
<td>R</td>
</tr>
</tbody>
</table>

*Denotes those of Hispanic/Latino heritage

3.3 Limitations

There are various conditions which influence the detection of sEMG signals, and these factors can be classified based on the level of influence on the signal:

- Technical: environmental conditions (temperature, humidity) and technical attributes of the equipment (electrode material and size, skin-electrode contact, amplifiers, filters)
• Experimental: measurement procedure (skin preparation, electrode orientation) and contraction conditions (exercise type, duration, muscle length)

• Descriptive: signal processing (rectification, signal features, parameters) and statistical analysis

• Physiological: characteristics of the neuromuscular system such as structure (diameter of the fibers, organization of fibers in the motor unit, filter properties of the tissue) or function (muscular coordination, fatigue, muscular composition)

While intramuscular EMG can be used to give localized or deep muscle activity, the requirements for conducting such tests was not viable for the scope of this research. The use of sEMG as the method of muscular activation was done so to reflect the current development of available electrodes and signal processing techniques for incorporation in non-medical settings and products. Additionally, the recorded EMG data is indicative of the muscular activation during task completion from the dominant arm of the participant, rather than of specific muscles in the forearm or hand. Without the use of imEMG, distinguishing between the superficial, intermediate, and deep compartments of the forearm would not be achievable.
4.1 Myo Armband

To generate the data that will be analyzed, a user wears the EMG sensor on their dominant arm. The sensor is the Myo gesture control armband by Thalmic Labs™. During use, the armband does not require any skin preparation such as removing arm hair or applying conductive gel. Myo is provided with eight EMG stainless steel medical grade electrodes, an inertial measurement unit, and a transmission module (see Figure 1). These electrodes create an 8-channel reading which is sampled at 200 Hz per channel. Recordings of muscle activation in previous works with the Myo armband have often been specified to a single electrode or averaged between a selection of electrodes for individual muscle testing (Hilt et al., 2021).

Figure 1. Myo Gesture Control armband
The Myo Armband was positioned on the participant with sensor 1 directed forwards from the user’s stance and/or in best tangential alignment with the frontal plane of the body. This placement aligned sensor 1 with the *brachioradialis* (see Figure 3).
4.2 TAR system

The users were asked to perform the same tasks while physically interacting with the objects directly and visually receiving feedback from a virtual interface of the objects. This TAR system was developed through Unity, a development platform for 2D, 3D, VR, and AR games and applications. With Unity, the Vuforia SDK was utilized as the main AR platform. The application was uploaded and run through a Google Pixel 3a smartphone.

The system simulated 3D models of the objects through a phone display to show their motions as they completed the tasks (see Figures 4 & 5). The 3D models resembled the physical interactions with the objects closely to accurately emulate the tangible feedback that would be given on the real object. Similarly, the objects used for interaction during the TAR task completion had the same scale, weight, and physical properties as those in the real-life tasks.
Figure 4. Unity software development

Figure 5. Image target recognition visual through downloaded application
CHAPTER 5. PROCEDURES

5.1 User Testing

Before beginning, participants were informed about the study and asked to sign the informed consent, as well as the pre-test questionnaire (see APPENDIX A). Then, the participants were briefed on sensors to be used in the study and the tasks they needed to perform. During this briefing the participants were informed of the type of sensory input and feedback they would receive. The user is fitted with the armband and receives instruction for the tasks prior to each task and subsequent recording. Though all values of the 8 channels from the Myo Armband were to be analyzed, a consistent orientation of the sensors was implemented to remove additional conditions that could alter recorded EMG data.

The first half of the task testing involved real-life, unaltered tasks that the participants performed as they would normally do in their daily life. When the participant indicated they were ready, the study began with the facilitator initiating the countdown for the first task to be performed and recorded by the EMG capture program. The recording also automatically cuts off after 1500 milliseconds (1.5 seconds), eliminating the need to later trim around the time when the task was completed. Participants did not practice the tasks prior to recording as the tasks were selected to require minimal instruction from the researcher for the users to understand and complete the actions. The tasks measured in this study include:

- removing the cap from a pen
- lifting a teacup from the table
- removing the lid from a disposable coffee cup

During each task, the participants were also instructed to conduct themselves in a manner most similar to how they would approach these tasks outside of the laboratory setting. Another requested instruction for conducting the tasks was to place their forearm(s) on the table surface (both forearms for the pen task, their dominant forearm for the teacup task, and their non-dominant forearm and dominant elbow for the coffee lid task) before starting at the researcher’s prompt. This was done to reduce EMG output stemming from the effort required to hold the limbs above the table surface or unnecessarily engaging with the weight of the objects prior to the task.

At the completion of the final real-life task, the participants were informed of the transition into the tangible augmented reality system task portion. In this, the change in input, feedback, and interaction method was explained to the participant before beginning the first TAR task. The participants observed their interactions through a phone screen mounted on a flexible stand in front of them. The orientation and position of the phone was adjusted to best fit their height and visibility for the table surface prior to beginning the first TAR task. Instruction for each TAR task was given prior to beginning the EMG data capture. At the end of the final TAR task, participants were asked to fill out the SUS survey, and thanked for their participation.
Figure 6. User testing of real-life tasks

Figure 7. User testing of TAR tasks
Each user undergoes 3 real-life task recordings and 3 TAR task recordings per session (see Figures 6 & 7) which are stored in a comma separated value (CSV) file with the raw EMG values. With the sampling rate for the recordings at 200 Hz over 1500 milliseconds, the CSV files produced consisted of an 8-column (for each EMG channel), 300-row (timestamped every millisecond) data set for each of the tasks.

5.2 Usability

The System Usability Scale (SUS) was used to measure the usability of the TAR system. SUS is an industry-based tool for measuring system usability, or the ease of use of an application. It consists of a 10-item questionnaire with 5 response options, ranging from “strongly disagree” to “strongly agree”. This method of measuring usability can evaluate a wide variety of products and services including hardware, software, websites, and applications. SUS is very easily administered and can be used with smaller sample sizes to differentiate between usable and unusable systems.

Calculating the scores from the SUS survey forms involves converting the scores from each question into a new number, depending on the question, adding the new numbers together, and multiplying by 100. The calculated scores from each questionnaire range from 0-100 and represent system usability, with the acceptable SUS score being 68. Though SUS is not a diagnostic tool, using this survey was to confirm that the gathered EMG data from the participants was not influenced by usability issues of the TAR system. The paper-based SUS survey was administered after the TAR task recordings and participants were instructed to score according to their experience solely with the latter half of the task testing (see Table 4).
### Table 4. SUS survey

<table>
<thead>
<tr>
<th>I think that I would like to use this system frequently.</th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neither Disagree nor Agree</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>I found the system unnecessarily complex.</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>I thought the product was easy to use.</td>
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</tr>
<tr>
<td>I think that I would need the support of a technical person to be able to use this system.</td>
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<tr>
<td>I think the design of the product is appealing.</td>
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<td></td>
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<td></td>
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<tr>
<td>I found that various functions of the system were inconsistent.</td>
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<tr>
<td>I imagine that most people would learn to use this system very quickly.</td>
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<tr>
<td>I found the system very cumbersome to use.</td>
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<tr>
<td>I think I could use the product without written instructions.</td>
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<td></td>
</tr>
<tr>
<td>I did not feel very confident using the system.</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 6. RESULTS

6.1 SUS Scores

The SUS score for the TAR system was 68.2, an acceptable score for usability as a supplemental device to the study. There are statistically no outliers in the SUS scores (see Figure 8 & Tables 5 & 6).

Figure 8. SUS score distribution
Table 5. SUS scores

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<tr>
<th></th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
<th>#8</th>
<th>#9</th>
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</tr>
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<td>4</td>
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<td>4</td>
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<td>66</td>
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</table>

Table 6. SUS score analysis

<p>| | |</p>
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<th></th>
</tr>
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<tr>
<td>Average SUS score</td>
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</tr>
<tr>
<td>Standard deviation</td>
<td>3.56</td>
</tr>
<tr>
<td>IQR</td>
<td>4</td>
</tr>
</tbody>
</table>
6.2 Significant Values

The purpose of the work was to determine the impact on EMG output from users while performing tasks in tangible augmented reality versus real-life. In the analysis of the EMG signals, the data collected in the CSV files was then rectified for analysis. This full-wave rectification converts the negative values from the signal to positive values and thus prevents the calculation of the signal’s mean output to come out to zero (see Figure 9).

Figure 9. Recorded EMG signal before and after rectification
The main features of EMG signal modeling used in comparison for this study were integrated EMG (iEMG) and waveform length (WL). Integrated EMG can be summarized as the area under the curve of the rectified EMG signal (Christopher, 2018). Waveform length is the cumulative length of the EMG waveform over the time segment. While both features are categorized as time-domain, iEMG is based on energy information (subclass 1) and WL is based on complexity information (subclass 2).

Other noted values from the EMG signal recordings in addition to iEMG and WL include minimum, maximum, mean, and range (see APPENDIX C). However, it has been observed in previous works that EMG signal features that fall into the frequency-domain grouping are often ill-suited to the classification of signals due to their dependency on one value taken from highly variable input and inability to represent the entire signal.

The data collected from the user testing was analyzed by participant and individual task for each of the focus values to determine potential impacts on EMG output from the TAR system. While maximum and mean values for the tasks both display generally higher values in TAR (19 for maximum value and 20 for mean value), it can be questioned whether a singular value (in the case for maximum) or the average of an oscillating signal (in the case for mean) can be appropriately reflective of EMG intensity. The changes in these values can be observed in APPENDIX D.

6.2.1 Integrated EMG

Recorded iEMG values of the users were compared between individual users, individual real-life tasks, individual TAR tasks, all real-life tasks averages, and all TAR task averages (see Figures 10 & 11). Of the 24 tasks performed by the users in real-life and
TAR, 15 tasks produced higher iEMG values in TAR. Though iEMG does not contain a unit of measurement, its value encompasses the duration of time while reducing the influence of the signal’s alternating characteristic.

Figure 10. iEMG task values
The difference between the average iEMG values for real-life and TAR tasks for each participant were observed as well (see Figure 12). The value change difference in iEMG from real-life tasks to TAR tasks had a minimum value of -1.421 and a maximum value of +8.620, with a mean of +3.445. The percent difference in iEMG values from real-life tasks to TAR tasks ranged between -8.43% and +62.264%, with an average percent increase for all tasks performed of +28.517%.
With the incorporation of the TAR system, 1 participant increased iEMG value in 1 out of 3 tasks, 8 participants increased iEMG value in 2 out of 3 tasks, and 9 participants increased iEMG value in all the tasks performed. While the average iEMG value for p4 (-.637) and p6 (-1.421) decreased in TAR compared to real-life both users only produced lower iEMG values in TAR for 1 of the tasks. This is likely due to the averaging of iEMG values for real-life vs TAR including all three of the tasks rather than repetitions of the same task. However, all 3 task types showed 3 users which produced lower TAR values.
P2 recorded lower TAR values in 2 out of 3 of the tasks, though their average iEMG value in TAR was still higher.

6.2.2 Waveform Length

As with iEMG, recorded WL values of the users were compared between individual users, individual real-life tasks, individual TAR tasks, all real-life tasks averages, and all TAR task averages (see Figures 13 & 14). WL for each of the 24 tasks produced 21 values that increased in with the TAR tasks. The value change difference in WL from real-life tasks to TAR tasks had a minimum value of +3.196 and a maximum value of +19.449 with a mean of +13.371. The percent difference in WL from real-life tasks to TAR tasks ranged between +15.582% and +213.828%, with an average percent increase for all tasks performed of +127.369%. There were no participants that only produced an increased WL value in 1 out of 3 tasks, while 6 participants increased WL value in 2 of the 3 tasks, and 12 participants increased WL value for all the tasks (see Figure 15).
Figure 13. WL Task Values

Figure 14. TAR WL task values
6.2.3 EMG feature comparison

Both iEMG and WL are time-domain features used for EMG signal analysis, though the two features are based on different information inputs and grouped into separate subclasses. In the comparison of these two features, there was exceptional correlation between iEMG and WL when observed for all 6 tasks (see Figures 16-21). The slight displacement from direct correlation in the real-life pen task ($r^2 = .895$) and the real-life coffee lid task ($r^2 = .947$) may be due to the difference in initial data used for calculation of iEMG and WL.
Figure 16. Real-life pen task iEMG and WL values

Figure 17. TAR pen task iEMG and WL values
Figure 18. Real-life teacup task iEMG and WL values

Figure 19. TAR teacup task iEMG and WL values
Figure 20. Real-life coffee lid task iEMG and WL values

Figure 21. TAR coffee lid task iEMG and WL values
The average values of iEMG and WL were found for all real-life tasks and all TAR tasks as well for each participant. The relationship between these two features displays significant correlation in the value difference from real-life to TAR: $r^2=.895$. There is likewise a significant regression slope for the percent change from real-life to TAR: $r^2=.853$ (see Figures 22 & 23).

Figure 22. iEMG and WL value differences
6.2.4 Assessment of Usability

The perceived usability of the TAR system and the values of TAR iEMG output for users was calculated as a percentage increase or decrease. Though 2 users reflected an overall iEMG decrease in TAR, there is a significant regression slope between the percent change and the SUS scores delivered by the participants: \( r^2 = .695 \) (see Figure 24). The percent change was used in this analysis rather than the value change as measured EMG values can vary greatly from person to person, and we were observing the change relative to the initial readings.
In the same manner, the percent change of the WL values from real-life tasks to TAR tasks were compared to the SUS scores by participant. Though there was a percent increase in WL value for all participants, there is a notably weaker regression slope between these two variables: $r^2 = .412$ (see Figure 25).

**Figure 24. iEMG % change and SUS scores**
Figure 25. WL % change and SUS scores
CHAPTER 7. CONCLUSION

This research has provided an overview of EMG and its current applications, identified techniques utilized in signal processing with the accuracy of those techniques as a tool for EMG measurement, and the condition of augmented reality systems today. These areas all display technological advances in past years which have enabled higher-quality readings, interpretation, and visualization of a user’s biomechanics in real-time. Results from this study are aimed at determining what impact utilizing a tangible augmented reality system has on EMG output of users performing motion-based tasks. Two time-domain signal features, integrated electromyography and waveform length, were compared based on individual participant, task, setting, and usability in the analysis of collected EMG data. The tasks performed by the users required minimal instruction and mental effort, and the satisfactory SUS score largely removes poor TAR system usability as an influence on the recorded EMG signals.

While the user data appears to indicate some level of increase in EMG output for both signal features when using the TAR system, there are still limitations when accurately collecting and interpreting sEMG signals. The TAR system solely utilized changes to the users’ visual interactions and can be improved to include a wider range of adjusted sensory input and feedback mechanisms for further study. Though limited in result capabilities, this study indicates an opportunity to explore areas to identify influences in muscular activation, as well as potential development of methods to incite specific levels of activation in users through augmented simulation (Jones & Kamper, 2018 & Kim, 2020). Specifically, there exists the potential for the application of electromyography in the
medical and physical therapy fields as a method of assessment, tracking, and creating a personalized and immersive standard for rehabilitation.
APPENDIX A. PRE-TEST QUESTIONNAIRE

Introduction:
• The purpose of this questionnaire is to gather subjects’ basic information.
• This survey has 6 questions and will take less than 10 minutes to complete.

1. What is your age?

2. What is your gender?
   o Male
   o Female
   o Other

3. What is your race?
   o American Indian or Alaska Native
   o Asian
   o Black or African American
   o Native Hawaiian or Other Pacific Islander
   o White or Caucasian
   o Two or more races
   o Other

4. Which arm/hand is your dominant side? (used for writing, tasks, etc.)
   o Right arm
   o Left arm

5. Do you have any motor limitations or injuries with your dominant hand/arm?
   o No
   o Yes

6. If yes, please explain:
APPENDIX B: USER TESTING GUIDE

Instructions: The items in normal text are the instructions for the study facilitator to read to the participant. Lines that are in brackets and bold are instructions for the study facilitator to follow. These are not to be read to the participant, but to indicate things that the facilitator needs to do.

Prior to the study session, all of the following should be done:

- Ensure all products, models, phones, sensors, tables/surfaces have been cleaned and sanitized
- Ensure that masks and sanitizer are available in the lab
- Have 2 printouts of the IRB approved Adult Consent Form
- Have 2 printouts of the Pre-Test Questionnaire
- Have 2 printouts of the SUS survey form
- Have 2 printouts of the Compensation Receipt form
- Have the 3 objects for task completion and the corresponding TAR task objects
- Have the Myo Gesture Control Armband charged and calibrated, with the backup armband available, and the EMG capture program set up
- Write the participant ID number on the top of the Pre-Test Questionnaire and SUS survey form]
[To begin after completion of Adult Consent Form]

[Study introduction and procedure description]

“Well, thank you for coming to participate in this study. I am conducting research on the impact of using tangible augmented reality and the muscular activation of users when completing motion-based tasks. For my testing, I will give you three different tasks to complete, first in an unaltered setting and then again while using a simple tangible augmented reality system. This system will alter the visual input you receive by looking through a display, but you will still be physically interacting with the products involved in the tasks otherwise. To measure your muscular activation, I will equip you with the Myo Gesture Control Armband which will be aligned on the forearm of your dominant hand during the tasks. This armband has 8 different sensors that record the electrical signals output from your arm and will log them in a file on the computer. During the tasks, you may experience some vibration feedback from the Myo Armband, but that is normal and is not harmful in any way. Do you have any questions so far?”

[Wait and allow for user to ask questions if necessary]

“Well, before I fit you with the armband, I will provide a short pre-test questionnaire to collect some basic information about you as a participant. This information will not be shared with anyone outside of the study nor be identifiable to you, as a participant, beyond the data collected from the questionnaire in the future analysis.”

[Provide the pre-test questionnaire and allow the participant to complete the form.]
“Thank you. Based on your feedback, you have identified your (right/left) arm as your dominant arm and you have no existing injuries or disabilities in regard to that arm, is that correct?”

[Allow for response and ensure the indication on the form matches the response for testing.]

“Okay, if you would please stand up, I will place the Myo Armband on your wrist. Rest your arm in a relaxed, natural position and leave it in that position as I orient the Myo Armband properly. The armband should be snug enough around your forearm that you do not feel as if it will slide off or detach during normal movement. As I bring the armband further up your forearm, let me know when it feels appropriately adjusted.”

[Position the Myo Armband on the participant with sensor 4 directed forwards from the user’s stance and/or in best tangential alignment with the frontal plane of the body. Ideally, this placement will align sensor 4 with the *brachioradialis*.]

[REAL-LIFE TASK TESTING]

“Now that the Myo Armband is placed, I will give you the tasks to complete for the study. I will provide instructions for each of the tasks before asking you to execute them, and if you have any questions or wish to stop the study at any time, please let me know. Do you have any questions before we begin?”

[Wait and allow for user to ask questions if necessary]
“For the first task, I will ask you to remove the cap of a ballpoint pen. In doing so, please pick up the pen in front of you and hold it with your non-dominant hand, the one not equipped with the armband. Rest your forearms on the table and place your dominant hand over the cap as if you are about to remove it. I will provide a countdown from 3, 2, 1, and go, and at “go” you can remove the cap from the pen as you normally would. Do you have any questions about this task?”

[Wait and allow for user to ask questions if necessary]

“If you are ready, then I will begin the countdown for the task.”

[Start countdown and enable Myo recording during pen task completion.]

“Thank you, now we can move to the second task. For this task, I will ask you to lift a teacup from the table. In doing so, please place your dominant hand over the cap as if you are about to remove it. As with the first task, start with your dominant forearm resting on the table. I will provide a countdown from 3, 2, 1, and go, and at “go” you can lift the teacup from the table as you normally would. Do you have any questions about this task?”

[Wait and allow for user to ask questions if necessary]

“If you are ready, then I will begin the countdown for the task.”

[Start countdown and enable Myo recording during teacup task completion.]

“Thank you. For the last task, I will ask you to remove the lid from a disposable coffee cup. Just as with the pen task, please hold the coffee cup with your non-dominant hand, the one not equipped with the armband while resting your forearm on the table. Place your
dominant hand over the lid in the most natural position for you as if you are about to remove it with your elbow resting on the table. I will provide a countdown from 3, 2, 1, and go, and at “go” you can remove the life from the cup as you normally would. Do you have any questions about this task?”

[Wait and allow for user to ask questions if necessary]

“If you are ready, then I will begin the countdown for the task.”

[Start countdown and enable Myo recording during coffee lid task completion.]

“Thank you. That completes the real-life unaltered task portion of this study. The second and last portion will be the completion of these same tasks but with the tangible augmented reality system.”

[TAR TASK TESTING]

[Position the phone stand in front of the user best fit to their height and vision for the task objects on the table with the TAR application open.]

“For these tasks I will place the individual objects in front of the phone camera at the start of each task, so your line of sight is through the phone screen. When the object’s image target is recognized by the TAR system, it will display an interactive 3D model of the task object to you. However, you will be physically completing the tasks in the same manner as with the real-life tasks beyond the screen. Do you have any questions about this portion?”
“Likewise for the first task, I will ask you to remove the cap of a ballpoint pen. As before please pick up the pen in front of you and hold it with your non-dominant hand, the one not equipped with the armband. Rest your forearms on the table and place your dominant hand over the cap as if you are about to remove it, ideally with minimal coverage of the paper image targets on the pen, as these are recognized by the phone camera and the TAR system. I will provide a countdown from 3, 2, 1, and go, and at “go” you can remove the cap from the pen as you normally would. Do you have any questions about this task?”

“If you are ready, then I will begin the countdown for the task.”

“Thank you, now we can move to the second task. Please place your dominant hand over the cap as if you are about to remove it. As with the first task, start with your dominant forearm resting on the table. I will provide a countdown from 3, 2, 1, and go, and at “go” you can lift the teacup from the table as you normally would. Do you have any questions about this task?”
[Wait and allow for user to ask questions if necessary.]

“If you are ready, then I will begin the countdown for the task.”

[Start countdown and enable Myo recording during TAR teacup task completion.
Remove the teacup from the camera’s field of vision after completion. Place the TAR testing coffee cup and lid with image targets on the table to allow the camera to identify the targets and generate the 3D models.]

“Thank you. For the last task, I will ask you to remove the lid from a disposable coffee cup. Similar to the pen task, please hold the coffee cup with your non-dominant hand, the one not equipped with the armband while resting your forearm on the table. Place your dominant hand over the lid in the most natural position for you as if you are about to remove it with your elbow resting on the table. I will provide a countdown from 3, 2, 1, and go, and at “go” you can remove the lid from the cup as you normally would. Do you have any questions about this task?”

[Wait and allow for user to ask questions if necessary.]

“If you are ready, then I will begin the countdown for the task.”

[Start countdown and enable Myo recording during TAR coffee lid task completion.]

“Thank you, that completes all of the testing for the study. I will now provide you with a survey for your feedback in regard to the usability of the TAR system. Please mark your answers to the corresponding boxes for what you feel best fits your experience and opinion about the TAR system while carrying out the tasks.”
[Provide the SUS survey and allow the participant to complete the form.]

“Thank you. You will be provided compensation for your time and will be asked to sign a receipt for receiving this compensation. Do you have any final questions about the study?”

[Answer any questions and provide the compensation and compensation receipt document and allow the participant to complete the form.]

“Thank you for your participation in this study.”
## APPENDIX C: NOTED EMG VALUES

### Table 7. Minimum EMG Values

<table>
<thead>
<tr>
<th></th>
<th>pen</th>
<th>TAR pen</th>
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<th>coffee lid</th>
<th>TAR coffee lid</th>
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# Table 8. Maximum EMG Values

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### Table 9. Mean EMG Values

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Table 10. Range of EMG Values

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Table 11. iEMG Values

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## APPENDIX D: PARTICIPANT DATA

Table 13. p1 data

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<td>max</td>
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<td>+0.375</td>
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<td>% difference</td>
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<td>0%</td>
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<td>+36.364%</td>
</tr>
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<td>+101.701%</td>
</tr>
<tr>
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</tr>
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<td>+11.985</td>
<td>+101.611%</td>
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<td>11.254</td>
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<td>+323.485%</td>
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Table 18. p6 data

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<td>+30.576%</td>
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<td>+49.971%</td>
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<td>+29.779%</td>
</tr>
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<td>+10.487</td>
<td>+49.981%</td>
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<td>+11.125</td>
<td>+25.501%</td>
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<tr>
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<td>+0.625</td>
<td>+35.714%</td>
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<tr>
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<td>+0.081%</td>
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<tr>
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<td>40.836</td>
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Table 19. p7 data

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<td>+0.42%</td>
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<th>% difference</th>
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<td>0.625</td>
<td>+0.125</td>
<td>+25.00%</td>
</tr>
<tr>
<td>mean</td>
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<td>+41.43%</td>
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<td>+10.375</td>
<td>+172.92%</td>
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<td>+0.375</td>
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</tr>
<tr>
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<td>11.268</td>
<td>15.026</td>
<td>+3.758</td>
<td>+33.35%</td>
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<td>+5.642</td>
<td>+33.42%</td>
</tr>
<tr>
<td>WL</td>
<td>15.616</td>
<td>45.078</td>
<td>+29.462</td>
<td>+188.67%</td>
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Table 24. p12 data

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<td>+64.07%</td>
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<td>4.852</td>
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<td>+69.43%</td>
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<td>+1</td>
<td>+133.33%</td>
</tr>
<tr>
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<td>4.928</td>
<td>6.872</td>
<td>+1.944</td>
<td>+39.45%</td>
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<td>22.625</td>
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<td>+2.915</td>
<td>+39.56%</td>
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<td>20.615</td>
<td>+5.8325</td>
<td>+39.46%</td>
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<td>25</td>
<td>34.375</td>
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<td>+37.5%</td>
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<td>6.155</td>
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<td>+32.67%</td>
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<td>32.75</td>
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<td>+38.62%</td>
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<td>9.213</td>
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<td>24.498</td>
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**Table 25. p13 data**

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<tr>
<td><strong>max</strong></td>
<td>23</td>
<td>55</td>
<td>+32</td>
<td>+139.13%</td>
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<tr>
<td><strong>min</strong></td>
<td>0.875</td>
<td>1.5</td>
<td>+0.625</td>
<td>+71.43%</td>
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<td>3.477</td>
<td>8.485</td>
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<td>+144.03%</td>
</tr>
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<td>22.125</td>
<td>53.5</td>
<td>+31.375</td>
<td>+141.81%</td>
</tr>
<tr>
<td><strong>iEMG</strong></td>
<td>2.707</td>
<td>12.378</td>
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<td>+357.26%</td>
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<td>+14.937</td>
<td>+151.82%</td>
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<th>% difference</th>
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<tr>
<td><strong>max</strong></td>
<td>8.75</td>
<td>20.375</td>
<td>+11.625</td>
<td>+132.86%</td>
</tr>
<tr>
<td><strong>min</strong></td>
<td>0.875</td>
<td>1.375</td>
<td>+0.5</td>
<td>+57.14%</td>
</tr>
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<td><strong>mean</strong></td>
<td>3.4</td>
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<td>19</td>
<td>+11.125</td>
<td>+141.27%</td>
</tr>
<tr>
<td><strong>iEMG</strong></td>
<td>5.088</td>
<td>10.735</td>
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<td>+110.99%</td>
</tr>
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<td><strong>WL</strong></td>
<td>10.201</td>
<td>21.546</td>
<td>+11.345</td>
<td>+111.21%</td>
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<td>32.25</td>
<td>43.375</td>
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<td>+34.50%</td>
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<td>+1.625</td>
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<td>+133.82%</td>
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<td>7.878</td>
<td>18.42</td>
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<td>+133.82%</td>
</tr>
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Table 26. p14 data

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<tr>
<td>max</td>
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<td>-9.375</td>
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<td>+87%</td>
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<td>4.48</td>
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<tr>
<td>WL</td>
<td>8.97</td>
<td>18.994</td>
<td>+10.024</td>
<td>+111.75%</td>
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<td>max</td>
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<td>23.25</td>
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<td>+41.98%</td>
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<tr>
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<td>-0.25</td>
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Table 27. p15 data

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<td>+58.44%</td>
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<td>+523.81%</td>
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<td>+285.29%</td>
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<tr>
<td>max</td>
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<td>+1.08%</td>
</tr>
<tr>
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<td>+0.125</td>
<td>+20%</td>
</tr>
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<td>2.958</td>
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### Table 28. p16 data

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<td>+17.78%</td>
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<td>-1.125</td>
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<tr>
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<td>7.781</td>
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<td>+50.37%</td>
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<td>-27.27%</td>
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<td>+65.82%</td>
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<td>8.799</td>
<td>+0.401</td>
<td>+4.77%</td>
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<td>+46.5%</td>
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<td>1.125</td>
<td>+0.25</td>
<td>+28.57%</td>
</tr>
<tr>
<td><strong>mean</strong></td>
<td>7.781</td>
<td>+0.669</td>
<td>+9.41%</td>
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<td><strong>range</strong></td>
<td>62.75</td>
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<td>+98.42%</td>
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Table 29. p17 data

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<td>+11.32%</td>
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<td>+16.5</td>
<td>+129.41%</td>
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### APPENDIX E: TASK DATA

Table 31. Real-life pen task data

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Table 35. Real-life coffee lid task data

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Table 36. TAR coffee lid task data

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REFERENCES


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