HHRI report
- Lab specialization -
EMG TORQUE AND POSITION CONTROL
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Contents

1 figures and tables

List of Figures

List of Tables

2 Introduction.

Electromyography (EMG) is a widely used technique that allows for non-invasive measurement of muscle activity using contact electrodes. EMG provides valuable information about muscle activation and can be used to control devices through muscle contractions.

The purpose of this lab is to acquire practical knowledge on EMG processing and acquisition, as well as subsequent applications for controlling a haptic paddle through muscle contractions. First, the EMG signal needs to be processed to better quantify muscle activity from raw data. Several steps and techniques will be applied to extract an easily analyzable waveform suitable for control purposes, known as an EMG envelope. Then, the processed EMG signal will be used to control the paddle through different strategies, either by directly changing the applied motor torque (torque control) or by changing the paddle's position using a PID controller (position control. Finally, the problem of muscle tremors will be addressed.

Through this lab, we aim to gain a deeper understanding of EMG technology in human-machine interfacing and biofeedback applications. Applications of such devices and control strategies range from prosthetics and rehabilitation robotics to entertainment technologies.

3 EMG signal - recording and processing.

3.1 Introduction to EMG and Hardware implementation.

Electromyography (EMG) is a frequently used technique for recording muscle activity from skeletal muscle. [2]
When a muscle is intended to be contracted, a signal is sent through motor neurons, initiating the contraction. Subsequently, an electrical signal travels along the muscle fibres. Electromyography involves detecting this signal by comparing the potential between two electrodes. A reference electrode can be employed to minimize noise and artefacts. EMG recording can be performed using surface or intramuscular electrodes, with the choice dependent on a trade-off between invasiveness and precision. When the surface electrode is chosen, a gel is applied to improve conductivity and reduce the skin-electrode interface impedance, improving the recording quality.

For this study, surface EMG is recorded using the Myoware muscle sensor kit [4], including two measure electrodes and a reference electrode. The signal is sent to the board, recorded and processed. The contact electrodes will be placed at one-third of the length of the bicep near the elbow crease and the reference electrodes will be placed on the bottom of the elbow on top of a bone, this position should maximally capture the bicep electrical activity under contraction and reduce the noise.

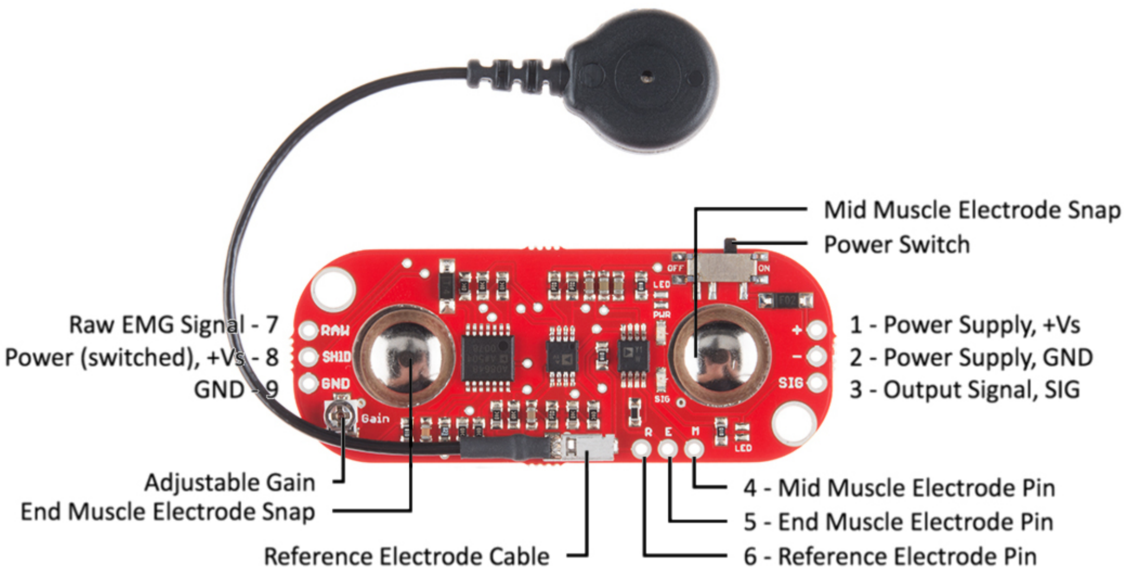


Figure 1: Myoware muscle sensor kit

3.2 Raw data and signal processing.

ANEMG signal can be very noisy, especially with small surface EMG similar to our devices. Several processing steps are applied to make the signal usable. While parameters such as electrode placement and contacts, muscle fatigue, and inter-subject variability greatly change the obtained signal, good processing can greatly reduce the noise and allow to obtaining of a proper signal. The aim is to extract a so-called "EMG envelope" that will best capture muscle activity with minimum noise. Moreover, the fluctuating battery of laptops can sensibly affect the EMG signal leading to the acquisition of even more noise, it is highly recommended to keep the devices plugged into the sector with a three-pin charger that provides a reference frame to not affect the signal too much.

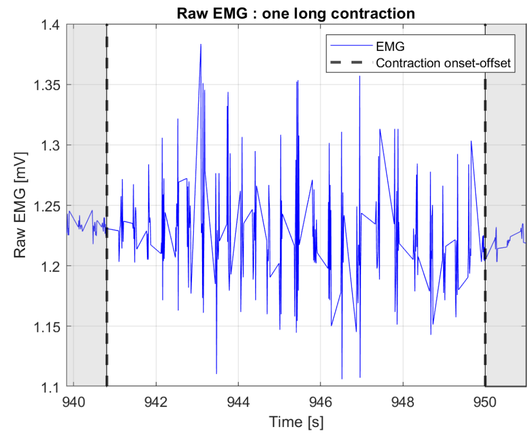
As a first step, the signal is band-passed between 150 and 200 [Hz], the lower bound mainly removes motion artefacts and power-grid noise while the upper bound removes high-frequency noise, overall it allows to extraction of only the relevant muscle activity.

As a next step, the signal is then rectified as it is wished to only see a positive increase in activity in the EMG signal during muscle contractions.

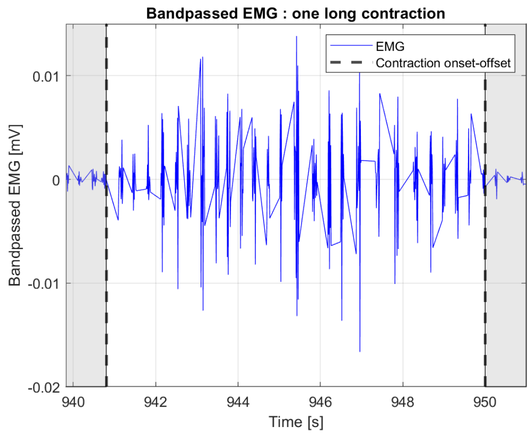
The EMG envelope can now be computed using the root a mean square (RMS) approach. The RMS is calculated through a moving window and is well suited for EMG as it gives a measure of the power of the signal and muscle contractions while providing a smoother waveform that is more easily analyzable. The RMS is computed on a moving average of the last 10 samples, **as the technique potentiates the signal, it now becomes unit-less**.

Finally, a threshold-specific gain is applied to once again eliminate noise and only amplify the contractions. The threshold is set at 0.00075, any values below will be set to zero while the values above will be amplified by a gain of 2.

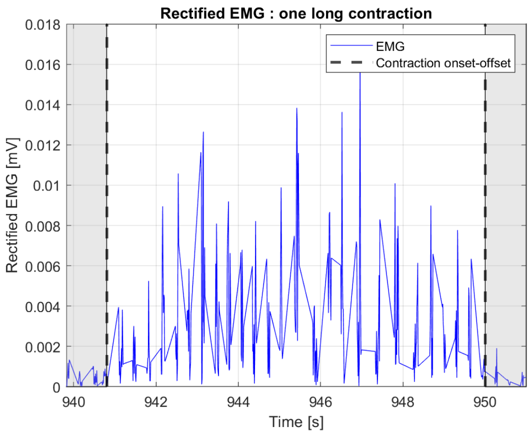
All sequential steps of EMG processing can be visualized for one long or multiple contractions (see Fig. 2 & 3), and processed EMG can be seen on top of the raw signal for better visualization for a long contraction, multiple contractions, and a relaxed muscle (see Fig. 4).



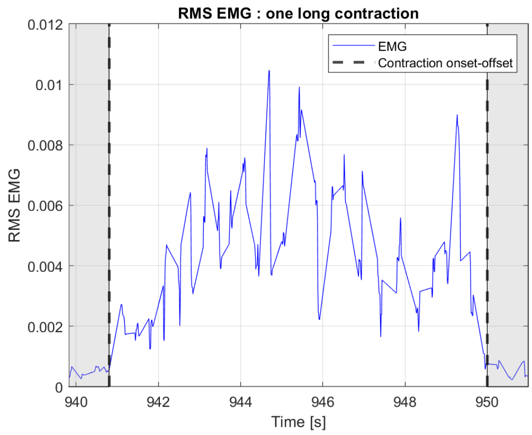
1: Raw EMG signal



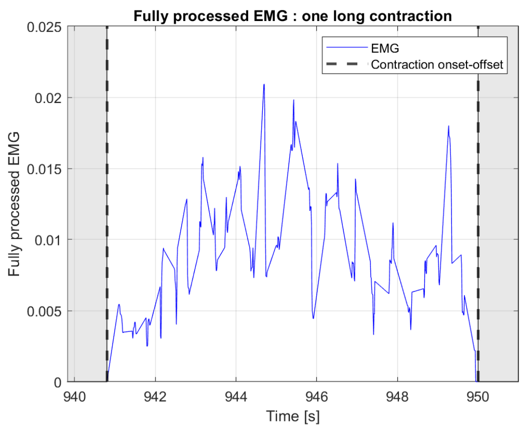
2: EMG band passed 150-200 [Hz]



3: Rectified EMG

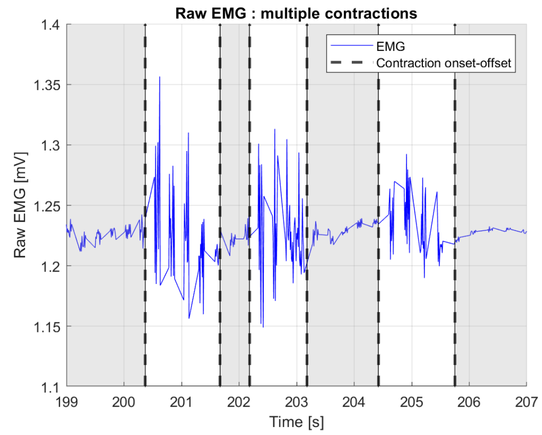


4: RMS EMG

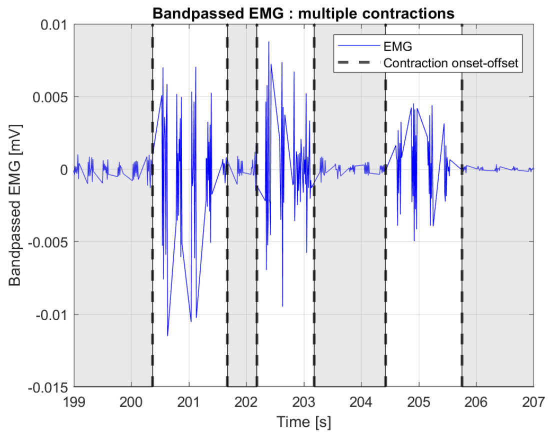


5: Fully processed EMG with threshold gain

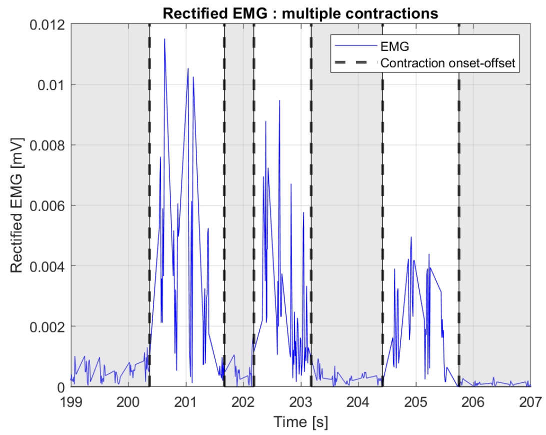
Figure 2: Visualization of the chronological steps of EMG processing for a long contraction.



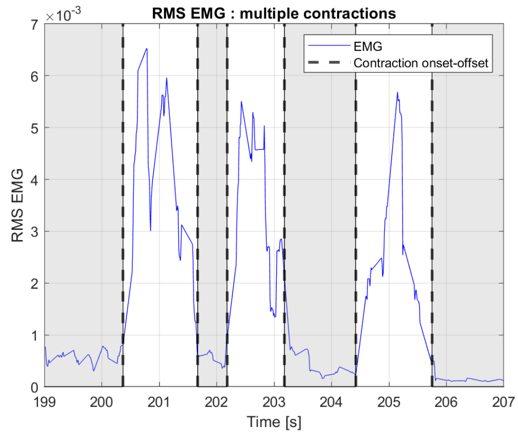
1: Raw EMG signal



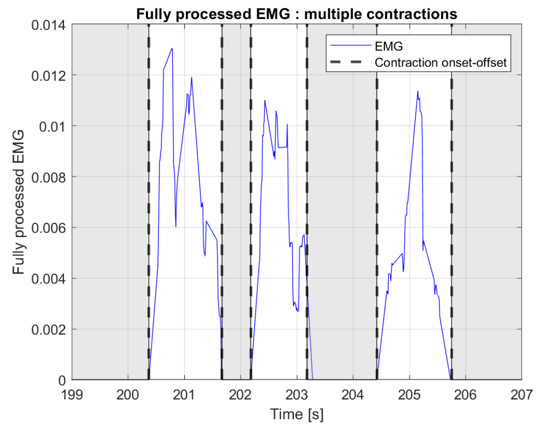
2: EMG band passed 150-200 [Hz]



3: Rectified EMG

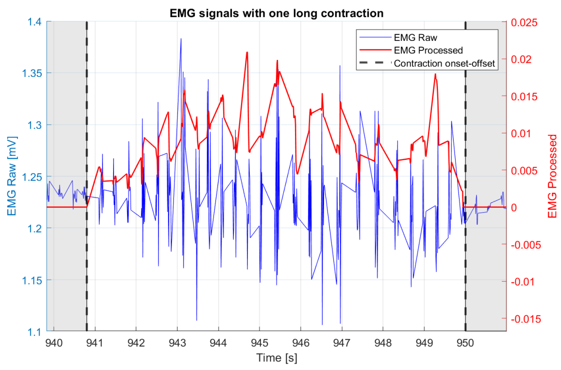


4: RMS EMG

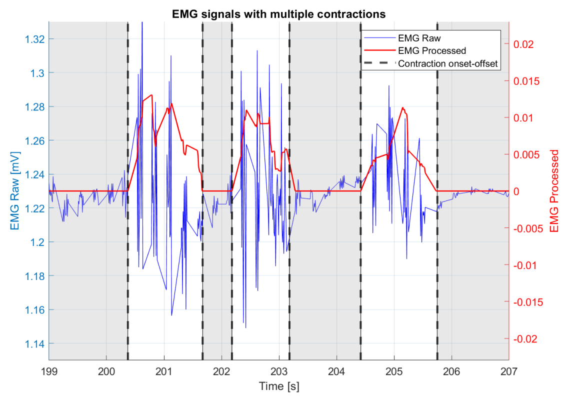


5: Fully processed EMG with threshold gain

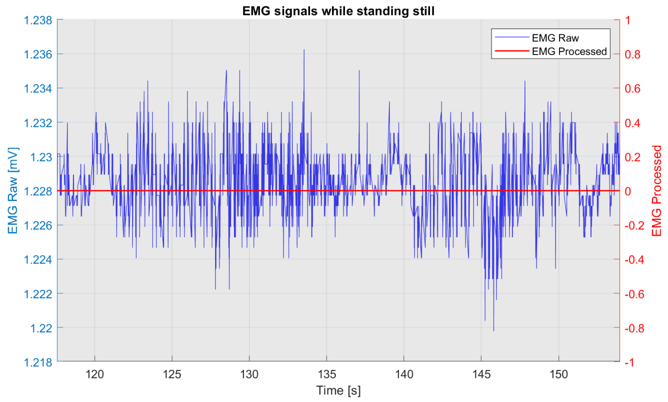
Figure 3: Visualization of the chronological steps of EMG processing for multiple contractions.



Long contraction.



Multiple contractions.



No contraction.

Figure 4: Comparison of post and pre-processed EMG for different conditions

4 Control Implementation.

4.1 Torque Control.

To implement torque control on the haptic paddle using EMG, the signal was first simply linearly mapped to the motor torque as such :

$$\tau_{motor} = EMG * 0.3 \tag{1}$$

As the range of the EMG goes from 0 at rest to 0.25 for a maximal contraction, this approach has been chosen to apply a torque that would be able to overcome the dry friction of the paddle and elicit movement without applying a torque too big that would dismount or break the cable. The gain has been tuned by hand to serve the wanted purpose. The motor torque hence falls in the 0-0.075 [nM] range.

Using this approach, a contraction high enough will elicit a motor torque able to exceed the dry friction and the paddle will start moving, if the contraction increases again the torque will increase along, and small contractions and movements will not elicit movement as the torque will be below the friction threshold. The paddle will only move in the clockwise direction and the position can be reset by hand.

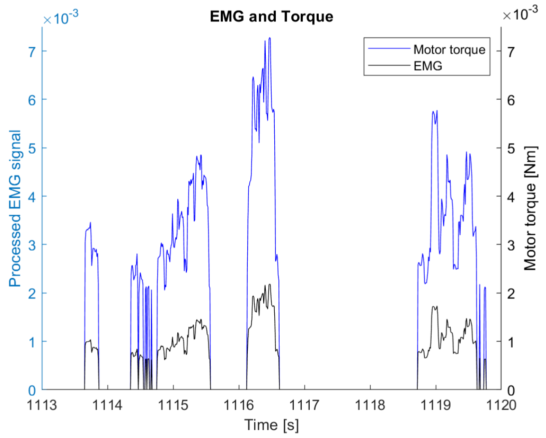
Plots to show the linear mapping between the EMG and motor torque and the initial implementation of torque control can be seen in Fig. 5. As visible, the torque closely follows the EMG signal up to a multiplicative gain. Big enough muscle contractions can elicit movement of the paddle through motor torque, and the position increases with EMG activity.

Further work has also been done on torque control for exploration purposes by implementing a kind of arm wrestling game with the paddle. In essence, the device always applies a negative torque proportional to how far the paddle is from its initial position as such :

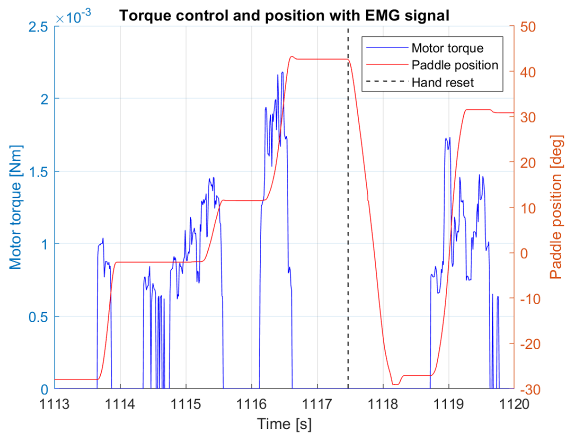
$$\tau_{motor} = -0.0001 * (PaddlePosition - \theta) \tag{2}$$

Where θ is the zero position (rest position), typically set to -15 degrees in the following experiment, manually adjusted at the beginning of the experiment.

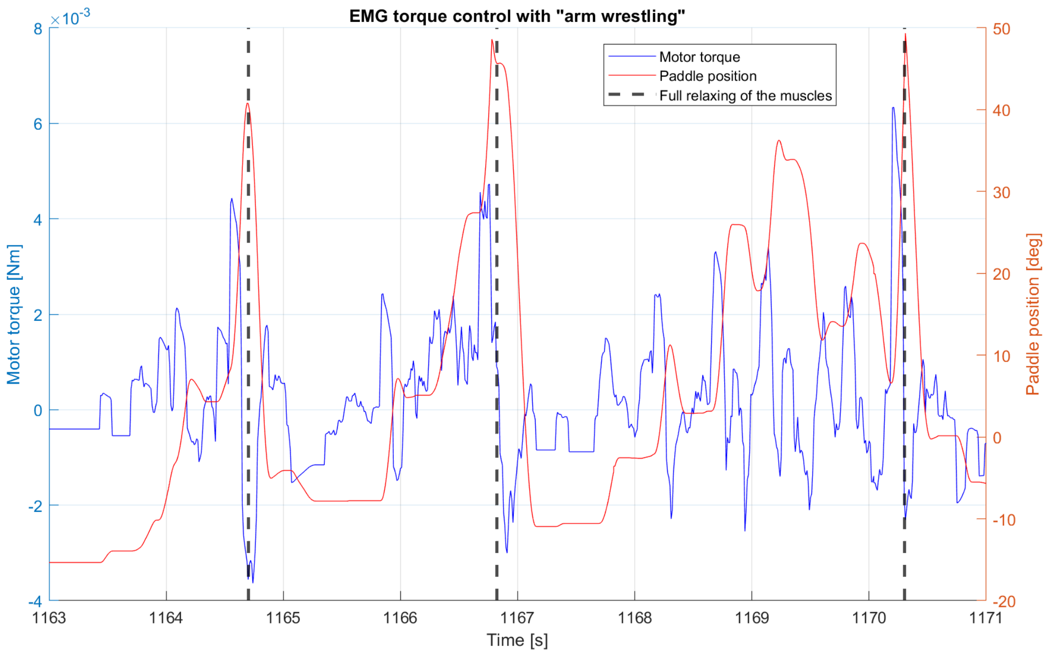
Hence the paddle will naturally move counterclockwise up to the initial position. The EMG signal is then used as before on top and participants can contract their muscles to fight against the motion of the paddle. Sustained contraction will be able to keep the paddle at a high position, and as soon as participants relax their muscles, the paddle will go back to its starting position. At no time the paddle is supposed to be touched directly and only muscle activity is used to control it.



EMG and torque signal.



Visualization of torque control.



Arm wrestle experiment with EMG torque control.

Figure 5: Assessment of torque control with EMG signal.

The result of the experiment can be seen in Fig. 5. With high enough EMG activity, the position of the paddle increases, but a full relaxation of the muscle will result in a negative torque putting the paddle back at its initial position. This experiment also allows us to test the torque controller without touching the paddle.

4.2 Position control.

To create a simple position control from the EMG signal, the first step is to map the signal range to the paddle angle range.

The paddle has an amplitude of 75 degrees. Based on experience, the EMG signal recorded never exceeds a value of 0.025 (after processing), with most of the values during a long contraction falling between 0.01 and 0.015, as seen in the processing step.

A full-range movement of the paddle for each contraction was not desired; instead, a smaller motion was preferred. The range [0, 0.025] was mapped to [0, 75] so that most contractions would fall within the range [0, 45].

The mapping is done as follows:

$$\underset{[\theta,75+\theta]}{Target\ Position} = \underset{[0,0.025]}{EMG} * 3000 + \theta$$

A PID controller was implemented following the same method as in previous labs. The Ziegler–Nichols method was attempted to find the best set of parameters but resulted in strong oscillations when the movement was initiated. The final PID values were hand-tuned and are shown in Table .1

name	**Kp (e-04)**	**Ki (e-04)**	**Kd (e-04)**
ZN	1.6	1.91	0.088
Hand tuning	1.8	0.01	0.1

Table 1: Parameters for the PID

4.3 Position control handling muscle tremor.

During long contractions, muscle fatigue, or due to certain disabilities, tremors can affect the stability of the signal, causing the paddle to oscillate, as observed with the first controller. This second controller aims to handle muscle tremors by making the paddle reach a precise position when a contraction is detected, remain stable, and return to the rest position after the contraction. To achieve this, most modifications were made to the EMG target position.

First, it was observed that the signal is highly unstable during contractions, but overall, it is high during the contraction and low in between. Therefore, a second RMS processing was applied to the signal using the values from the processed EMG and a larger batch size. Several values were tested, and a batch size of 25 produced the best results.

The initial processing smoothed the signal, yet it still exhibited some variation. To address this, a step function was applied to the EMG signal. Steps of 10, 15, and 20 degrees were tested experimentally, and 15 degrees was found to be a good compromise.

The new target position is calculated as follows:

$$\underset{[\theta,75+\theta]}{Target\ Position} = stepFunction(\underset{[0,0.025]}{rms(EMG, bufferSize)} * 3000 + \theta)$$

An example of the processing can be found in Figure 6. The resting position was -15, the increment was +15, and the maximum range of the paddle was [-15, 60]. Most of the target range falls between -15 and +15.

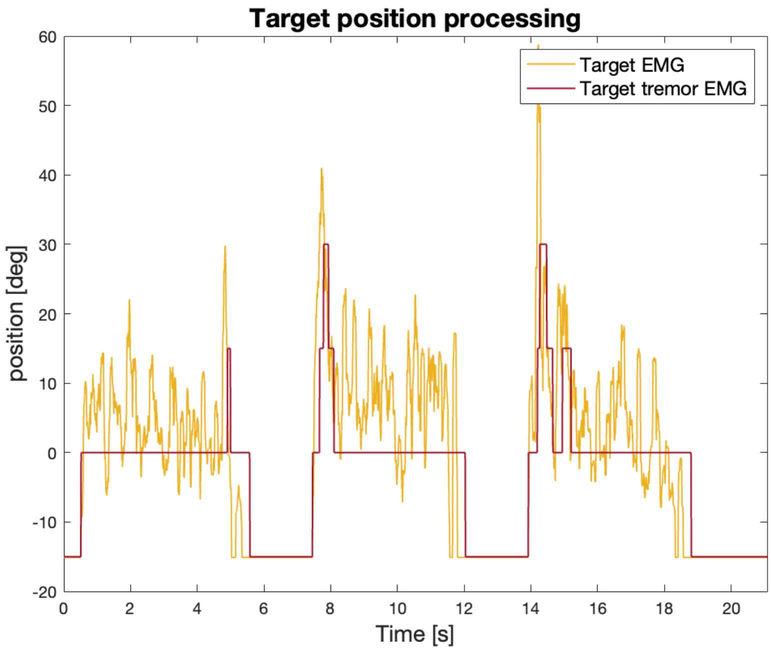


Figure 6: Target position with and without tremor handling

5 Results of position control with and without muscle tremors.

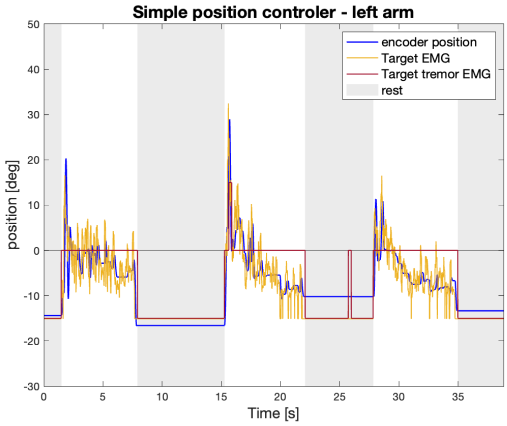
An experiment was conducted to compare the efficiency of a simple position controller versus an optimized position controller designed for muscle tremors.

Two subjects were asked to perform three long contractions (lasting between 5 to 10 seconds) with short rest periods in between. The experiment was carried out using both arms of each subject, testing both the simple position controller and the optimized position controller each time. The results for each of the subjects can be found in Fig.7 and Fig.8.

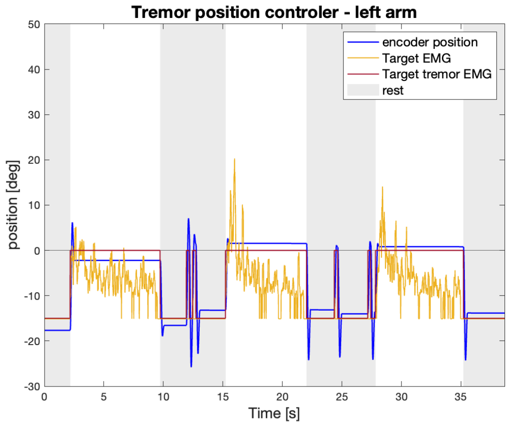
On the left side of the graphs, the paddle (encoder position, blue) has the mapped EMG (Target EMG, orange) as its target. On the right side, the target is optimized for tremor (target tremor EMG, red).

To analyze the error between the paddle position and the target, the RMSE (Root Mean Square Error) between the target and the signal was calculated. Since it was more important to provide a controller that is stable and can reach a particular position when a contraction is detected, stability was prioritized over precision. To assess stability, the contractions were extracted (shown in white on the graphs) and the standard deviation of the signal during the contractions was calculated. A small standard deviation indicates a stable signal.

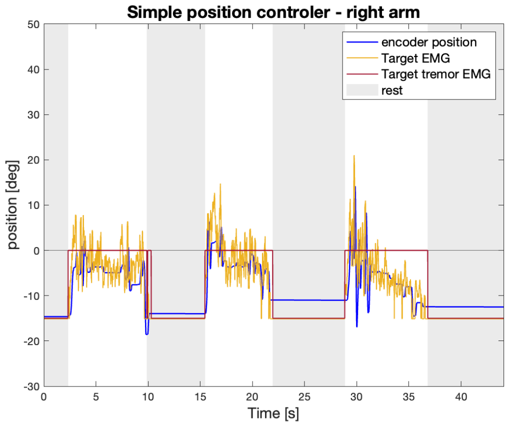
The mean of the standard deviation of the three contractions was used to assess stability. The results can be found for each of the subjects in Table.2 and Table.3.



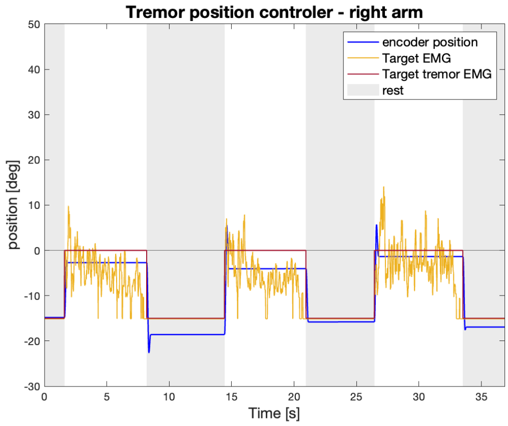
Left arm



Left arm optimised



Right arm

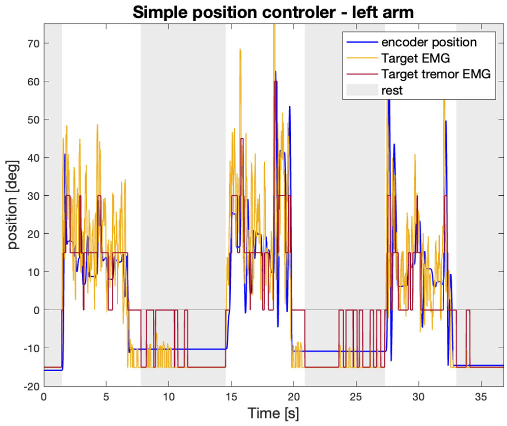


Right arm optimised

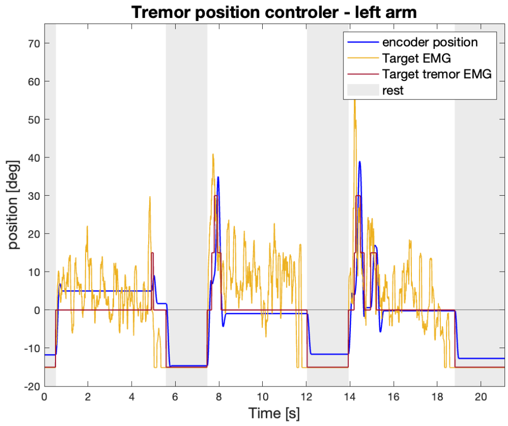
Figure 7: Result of the experiment - Subject 1

	simple left			optimised left			simple right			optimised right		
RMSE	4.1388			3.084			3.9849			3.0088		
mean STD	3.9011			1.4455			5.289			1.457		
STD per contraction	3.22	3.64	4.84	1.12	1.71	1.43	4.69	6.71	4.47	1.59	1.47	1.35
length of contraction (min)	7.55	6.5	7.95	6.59	6.52	7.09	6.44	6.82	7.15	7.57	6.91	7.39

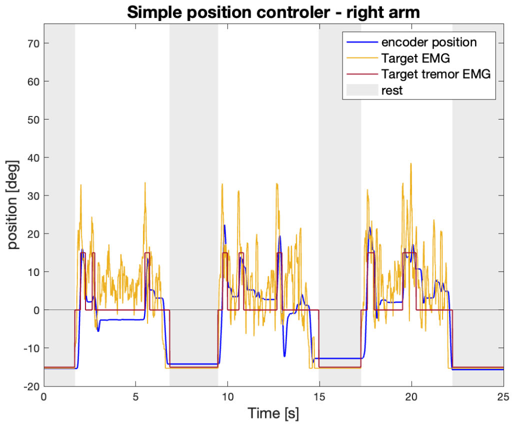
Table 2: Recap of the result for subject 1



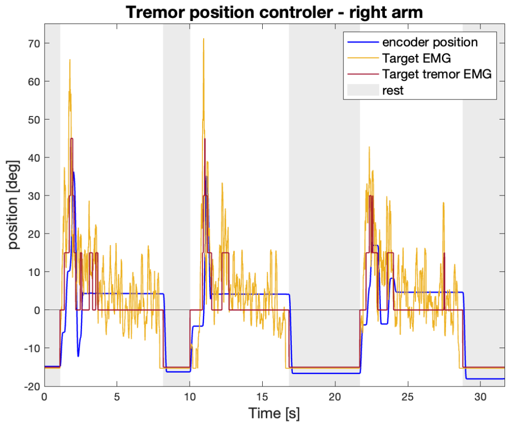
Left arm



Left arm optimised



Right arm



Right arm optimised

Figure 8: Result of the experiment - Subject 2

	simple left			optimised left			simple right			optimised right		
RMSE	8.6037			6.3742			13.637			4.5574		
mean STD	6.9182			6.1955			14.102			5.5121		
STD per contraction	5.96	7.58	7.22	6.89	6.47	5.23	10.84	17.31	14.15	2.12	6.63	7.79
length of contraction (min)	5.16	5.49	4.98	7.1	6.81	7.08	6.34	6.34	5.73	5.06	4.58	7.88

Table 3: Recap of the result for subject 2

For the two subjects, the tremor position controller is visibly more stable. With the simple controller, the paddle tries to follow the changes in the amplitude of the EMG. Muscle fatigue is observable along the contractions (the last contraction is noisier and weaker than the first contraction), especially in subject one. With the tremor controller, the paddle overshoots at the start of the contraction and then reaches a plateau. After less than a second, the paddle remains stable throughout the contraction.

For subject one, the standard deviation was reduced by more than half, indicating a significant gain in stability. The RMSE is also lower, indicating increased precision.
For subject two, the standard deviation was reduced by three times for the right arm, with a similar effect observable in the RMSE. The control is more stable and more precise. For the left arm, the RMSE is reduced, but the standard deviation difference is not significant. However, strong overshoots are visible in this case, influencing the standard deviation. Additionally, these contractions were longer.

The PID controller isn't extremely precise; this is especially noticeable with the first subject using the tremor controller, where the controller tends to stay at a value close to the target and does not adjust after the initial strong movement. However, since stability was the main goal, this level of precision was considered sufficient.

Artefacts are visible in the graph for the optimized left arm of the first subject and in the graph for the left arm of the second subject. These artefacts are mainly due to the degradation of the electrode gels after multiple experiments. The artefacts affect the tremor-optimized controller more than the simple controller. A final subject was tested, but the results were inconclusive as the gel was too degraded to function normally.

6 Applicability in prosthesis.

Control of devices through muscle activation offers numerous possibilities in the field of prosthetics.

EMG is already utilized for myoelectric control of prosthetic limbs, primarily arms and hands [3, 1]. It provides a direct link to the central nervous system, enabling biomimetic and more intuitive control.
The implemented position and torque control could be utilized to control prosthetics, for instance, using multiple EMG signals on residual muscles. In such cases, precise position control would offer better accuracy.
Position control can also be applied to exoskeleton control, where precise control and processing are essential. Muscle activity needs to be mapped to the range of motion and each degree of freedom of the exoskeleton [7].
Similarly to prosthetic control, EMG control could enhance human body capabilities, such as controlling an additional limb [5, 6].

In all these applications, position control provides more precise movement control. Particularly, a controller capable of handling muscle tremors could be more precise and useful in cases such as prosthetics or exoskeletons for tremor-affected individuals, especially those with diseases like Parkinson's or various muscle weakness and neurological disorders. On the other hand, torque control is faster and more reactive, suitable for less precise tasks.

7 Conclusion.

This report explored the potential of EMG signals for controlling haptic devices. The signal was processed through a band-passed filter between 150-200 [Hz] and rectified before the final envelope was computed using RMS and a threshold-specific gain to provide an easily identifiable waveform suitable for control purposes.

The obtained signal was used to control the motor torque of the haptic device through a linear mapping between EMG amplitude and torque, this allowed to move the paddle through muscle activity. Using this approach, a fun little arm wrestling game has also been implemented with the paddle applying an opposite torque that the person in control needs to oppose by contracting their muscles.

Additionally, a subsequent position control is proposed utilizing a hand-tuned PID controller that sets the target position as a function of the EMG signal. Further work has been conducted to address muscle tremors, enabling the system to achieve precise positioning and maintain stability.

While both of these control policies work pretty well thanks to the well-processed EMG and well-thought implementation and tuning, the mapping between the EMG signal and torque/position should not have been done with the entire range. Current implementation forces the participants to fully contract their muscles to reach maximum torques and higher positions and it can lead to a lot of muscle fatigue if this has been used for a very long time such as a prosthesis. Further work should remap the EMG signal to be able to have big effects on the device without fully contracting muscles to avoid fatigue and a decrease in performance.

The reported results of this lab demonstrate how EMG technology can be used for biofeedback and human-machine interfacing applications, but also in virtual reality and entertainment technology for interactions with a virtual environment with an input depending on the force applied. However, EMG is mostly used thanks to its non-invasive nature but the signal can become greatly unreliable and intra-neural measurements might be more suited for fine dexterity tasks.

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