Enhancing Musculoskeletal Injury Rehabilitation and Prevention in Rural Areas

Exploring Vibrotactile Feedback Usage in Rural Areas

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TU Delft

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Enhancing Musculoskeletal Injury Rehabilitation and Prevention in Rural Areas: Exploring Vibrotactile Feedback Usage in Rural Areas

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***Abstract*—Shoulder injuries, prevalent worldwide, often occur from ageing and accidents. In Western countries, these injuries primarily afflict the elderly population, while in rural regions of Bangladesh, Iran, India, and Pakistan, they affect younger individuals who are often the family's primary earners. Due to that, preventing and aiding the recovery of shoulder injuries is crucial. To address this, strain maps with vibrotactile feedback, emerge as a promising solution. However, the feedback system must be affordable, compact, comfortable, user-friendly, easily understood, and portable to suit the local environment. Vibrotactile feedback appears promising but can distract the user from work. Hence, this study seeks to investigate if vibrotactile feedback can be paired with strain maps to guide users in maintaining healthy postures and reducing the risk of shoulder injuries in rural areas, where visual feedback is used as a benchmark. To provide feedback using strain maps, shoulder angles are determined using Python's OpenCV and MediaPipe libraries. PyGame is utilized to display the strain maps, and OpenCV helps delineate boundaries between regions of high and low strain within the shoulder. Visual feedback is integrated into the strain map display, while vibrotactile feedback is delivered through a wearable haptic device. Despite challenges related to axial rotation accuracy and the camera-dependent nature of shoulder angle measurements, user experiments, conducted independently for shoulder elevation and planar elevation, reveal that vibrotactile feedback shows better performance compared to visual feedback. Consequently, this study concludes that vibrotactile feedback has the potential to prevent shoulder injuries with strain maps, but also still needs to improve for future work.**

***Index Terms*—Shoulder Injuries, Vibrotactile Feedback, Visual Feedback, Rural Areas, Strain Maps, MediaPipe, OpenCV.**

I. Introduction

Shoulder rotator cuff injuries rank among one of the most common injuries in the world and primarily occur due to accidents and ordinary wear and tear due to ageing[1]. However, the prevalence of it varies over multiple places. In [2], the incidence rate of shoulder injuries is about 22.1% in a village in Japan. Although, in this study, the mean average age was 69.5 years. Even in Western countries, the prevalence of shoulder injuries differs between 6.9% and 26%, which also mainly occurs around the age group of 70 years[3]. However, in rural areas, shoulder injuries mainly occur within younger age groups. According to [4], 6.2% of the population in six villages near Dhaka(Bangladesh(figure 1)) have musculoskeletal pain and disorders in their shoulders and mainly occur within the age group of 35-44 years. In addition, other rural areas have more cases where the population suffers from shoulder injuries. In the Hamadan province in Iran(figure 1), 22.7% of the population had problems with their shoulder where the group age was mainly between 15-29 years[5]. In the rural areas in the Kanpur district in Uttar Pradesh India(figure 1), 22.0% of the farmers suffer from shoulder pain, where the average age of the study was 42.4 years[6]. Lastly, 48.3% of the farmers from the Swat, Peshawar and Kohat Districts in Khyber Pakhtunkhwa Pakistan(figure 1) are also suffering from musculoskeletal pain and disorders in their shoulders where the median age is 35-50 years[7]. So, it can be observed that in rural areas, the younger population are more suffering from musculoskeletal pain and disorders compared to the elderly population. For these age groups, it is crucial to recover them from the injuries and pain they got in their shoulder and prevent them from further pain, injuries, and disorders in the shoulder, since they are the main workforces within their country and family.

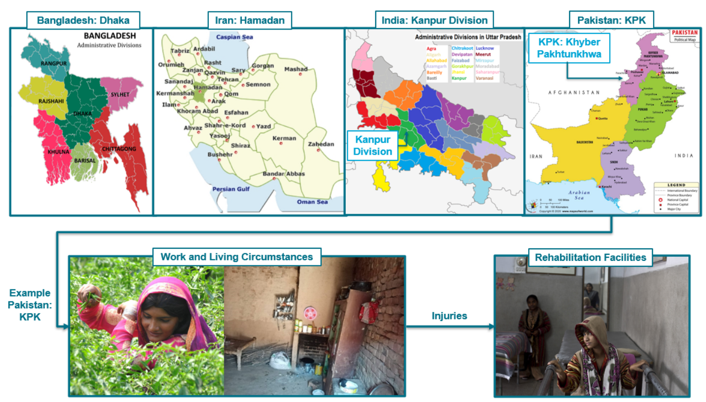

Fig. 1. Example of the work and living circumstances of farmers in the Khyber Pakhtunkhwa province of Pakistan[8][9].

A. Strain Maps

Both [1] and [10] show a novel method to decrease and rehabilitate shoulder injuries based on strain maps. In these papers, the strains of the rotator cuff(RC) muscles/tendons are determined based on the shoulder configuration, external forces, and muscle activations of the bio-mechanical model given in figure 2. In this instance, the shoulder configuration is determined by the bio-mechanical model's shoulder elevation, planar elevation, and axial rotation, which are also shown in figure 2. As a result, using the given parameters provided, it will produce strain intensities that rely on the model's axial rotation, planar elevation, and shoulder elevation, where the planar elevation is on the x-axis and the shoulder elevation is

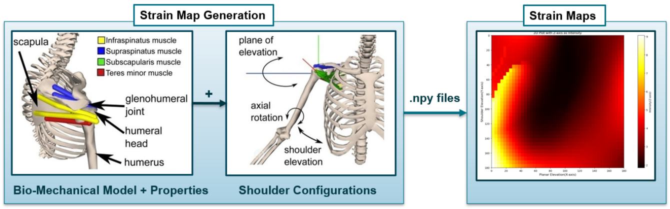

Fig. 2. Process of strain map generation[10].

on the y-axis. In order to prevent shoulder musculoskeletal problems, the strain maps are able to provide an intuitive representation of the RC tendon strain that may be utilised as a real-time, high-resolution estimation of the muscle strains. Due to that, this can be seen as a potential to decrease musculoskeletal injuries of the shoulders in rural areas and other areas.

B. *Vibrotactile, Audio, and Visual Feedback*

Wearable haptic devices have generated a lot of interest due to the manner in which they perform for a variety of purposes, including communication, health, and entertainment[11][12]. In this case, vibrotactile feedback is the most common type of haptic feedback and has shown that it can work on multiple surface areas of the human body in multiple real-time applications. Despite that, it has also shown that it is able to provide guidance during navigation tasks and safety signals in various applications[13]. However, wearable devices based on vibrotactile feedback can disturb humans in their specific tasks and can take time to set up the wearable device[14]. Other ways to provide feedback to humans are audio and visual feedback. Both types of feedback do not necessarily need to be equipped on the body and cannot disturb the human from a physical perspective. However, they both have their disadvantages as well. In audio feedback, the human can fulfil tasks without turning his/her head towards a display, however, giving pose correction with audio is slower compared to the other methods and is hard to perceive when it is given in a noisy area. Visual feedback is faster, but the human needs to check a given display to perceive the given feedback. So, every type of feedback has its own characteristics and needs to be selected based on the environment in which the human needs to complete its specific task.

C. *Research Question*

As previously noted, musculoskeletal injuries and disorders are often noted within the younger population in certain rural areas in Bangladesh, Iran, India, and Pakistan. They are the workforces within these countries and their own families. So, it is crucial to recover them from the injuries and pain they got and they should be prevented from further pain, injuries, and disorders in the shoulder. However, preventing them from these problems is a challenge. In most of these rural areas, only basic healthcare facilities are available(e.g. figure 1)[15]. More advanced healthcare facilities are in urban areas, which makes it more expensive for the population within rural areas[16]. Additionally, in Bangladesh, India, Iran, and Pakistan, rural areas are also in hilly areas, deltas, and deserts with poor infrastructure, which makes it hard to reach more advanced healthcare facilities in urban areas[15]. So, a home-based rehabilitation setup would be more cost-effective[17]. Despite that, poverty mostly occurs in rural areas where the people suffer from the highest rates of deprivation(e.g. education, health, and energy supply)[18]. Lastly, most of the population who are living in rural areas also suffer from high workloads with labour-intensive work to earn their income[7]. So, in summary, the following main challenges can be listed for the prevention of shoulder injuries in these rural areas:

- Logistical Issues
- Low Income(e.g. 30000-50000 PKR = 94.8-158.0 EUR per month)
- Low Education Quality
- Work Circumstances

One potential solution to decrease musculoskeletal injuries of the shoulders in this field can be strain maps. These maps can be used to provide feedback to the people in rural areas to prevent musculoskeletal injuries through various options. One of the more affordable options to provide the given feedback are vibrotactile feedback, audio feedback, and visual feedback. Each type of feedback mechanism has its own advantages and disadvantages and should be chosen based on the given environment in which it should be performed. As earlier observed, the population in rural areas have in most cases a low income, poor infrastructure and logistical facilities, high and intensive workload, and a poor educational background. Due to that, an affordable, compact, comfortable, simple to use, comprehend, and portable solution should be created to rehabilitate and prevent people from musculoskeletal shoulder injuries and pain. Additionally, it would also help if the solution could be used during their working time. So, based on these observations, vibrotactile feedback together with the strain maps as a feedback mechanism can be seen as a potential solution since it can be made affordable, wearable, wireless, compact, comprehend, and portable. However, it can also disturb the users from their tasks. Due to that, in this study, visual feedback will be used as a benchmark to investigate the potential of vibrotactile feedback. Audio feedback is not included due to its poor response time and the fact that it is difficult to use in rural regions where workers are exposed to high noise pollution[7]. So, based on previously given observations, this study will answer the following research question:

Can vibrotactile feedback be paired with strain maps to guide users in rural areas to reduce the risk of shoulder injuries and maintain healthy postures?

II. Methodology

A. *Human pose estimation*

Tracking the shoulder angles is crucial for observing the motion of the patients which is used to provide feedback to guide the patients towards favourable motions based on the strain maps[19]. The shoulder angles can be tracked with either wearable-based methods or with computer vision-based methods. In this study, wearable-based human pose tracking methods are not used since these methods are expensive and not flexible[20]. Computer vision-based methods are more flexible and do not require markers. Due to that, computer vision-based methods are an ideal solution to track the shoulder angles for the strain maps for this study. In most of the cases, it is based on open-source cross-platform frameworks that are used to compute 2D/3D human joint coordinates estimations for each image frame using machine learning (ML)[21][20]. A list of popular open-source pose estimation libraries can observed below[22][23]:

- Openpose
- Movenet(Posenet)
- Alphapose
- MediaPipe(Blazepose)

In this study, MediaPipe is used since it is user-friendly, relatively accurate, supports multiple programming interfaces, and is easy to use on laptops, mobiles and other devices[24][23]. This will be used together with OpenCV. OpenCV is also an open-source library but for computer vision written in C++. Nevertheless, it also has an application programming interface(API) which makes it possible to use it in Python[25]. In this study, OpenCV is used to track a real-time video of the given environment with the installed webcam of the laptop(figure 4). So, together with MediaPipe(figure 4), it will track the human posture in real-time where OpenCV is responsible for tracking the environment in real-time, and MediaPipe for tracking and obtaining the body coordinates of the MediaPipe model given in figure 3.

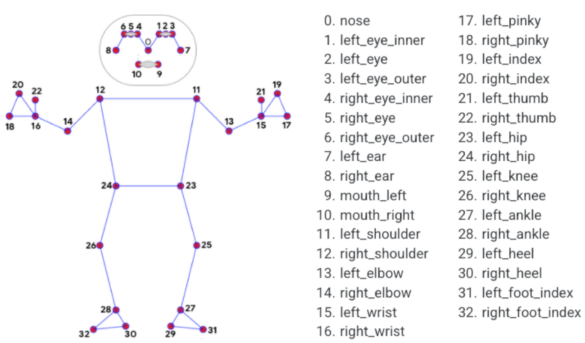

Fig. 3. Landmarks of the MediaPipe model[24].

These provided coordinates can be used to calculate the shoulder angles. For all given shoulder angles, the angles can be computed with the Pythagoras theorem and cosine theorem as follows[26][27]:

$$a = \sqrt{(x_2 - x_3)^2 + (y_2 - y_3)^2 + (z_2 - z_3)^2} \tag{1}$$

$$b = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2 + (z_3 - z_1)^2} \tag{2}$$

$$c = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{3}$$

$$\theta = \arccos(\frac{c^2 + b^2 - a^2}{2bc}) \tag{4}$$

In these equations, the measured x(x_1,x_2,x_3), y(y_1,y_2,y_3), and z(z_1,z_2,z_3) coordinates are used in equation 1, 2, and 3, to compute the the perpendicular length(a), base length(c), and the hypotenuse(b). Based on these lengths, the cosine theorem is used to compute the desired shoulder angle in equation 4. Each shoulder angle is calculated using a separate set of body coordinates. The shoulder elevation angle is calculated using the coordinates of the left hip (Landmark 23), left shoulder (Landmark 11), and left elbow (Landmark 13) for the left arm and the right hip (Landmark 24), right shoulder (Landmark 12), and right elbow (Landmark 14) for the right arm. For the planar elevation, the left shoulder (Landmark 11) and right shoulder (Landmark 12) represent the collarbones, and in combination with the left elbow (Landmark 13) or right elbow (Landmark 14) the planar elevation angle is computed for the left and right arm respectively. Lastly, the axial rotation angle is calculated from the coordinates of the left shoulder (Landmark 11), left elbow (Landmark 13), left index finger(Landmark 19) for the left arm, and the right shoulder (Landmark 12), right elbow (Landmark 14), and the right index finger (Landmark 20) for the right arm.

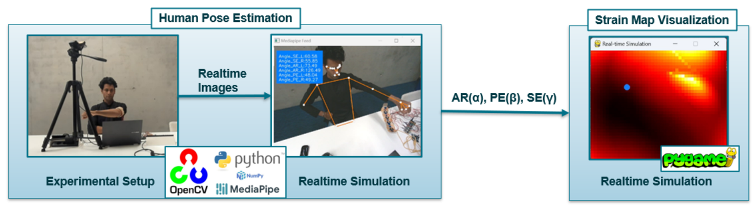

Fig. 4. Realtime process of the human pose estimation with Mediapipe, including the computed shoulder angles used for the strain map visualization.

When the shoulder angles are computed, they will be shown in a blue rectangle box on the left of the MediaPipe Feed display. In this case, Angle_SE_L and Angle_SE_R are the shoulder elevation angles for the left and right arm respectively, Angle_PE_L and Angle_PE_R are the planar elevation angles for the left and right arm respectively, and Angle_AR_L and Angle_AR_R are the axial rotation angles for the left and right arm respectively. Additionally, the landmarks(white) including the connected lines(orange) between them are also displayed on the MediaPipe feed to give the user an overview of the human pose estimation in real-time. After that, the computed shoulder angles will be used within the strain map visualization(figure 4).

B. Strain Maps and PyGame

As mentioned earlier, strain maps are able to be used for real-time, high-resolution estimation of muscle strains based on shoulder angles. In this study, the strain maps were given in npy(NumPy array) files and converted to images(figure 2). After this, these images were used to display the strain maps in real-time with PyGame. PyGame is a set of Python modules designed for writing video games, but can also be used to simulate other real-time videos[28]. In this case, it is used to display the strain maps in real-time together with the MediaPipe video display given in figure 4. Unfortunately, the npy files could not be directly used to generate the strain maps, since it increases the computation time in the code, which slowed down the processes of the code. Due to that, images are generated from the npy files and used to generate the strain maps. However, with this method, the strain intensity numbers cannot be used to create a threshold between safe and unsafe regions, since the npy files are transformed into images. Nevertheless, the images can be segmented in real-time with OpenCV and generate boundaries between the unsafe and the safe regions of the strain maps based on the given threshold and the colours of the image. An example

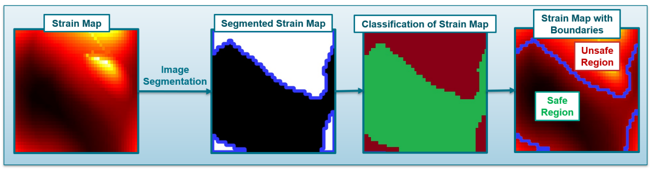

Fig. 5. Process of generating a safe region and unsafe region with image segmentation of strain maps to prevent high shoulder strain intensities(threshold = 60).

of image segmentation process can be observed in figure 5. In this case, the black region represents the safe region with low strain intensity rates and the white region represents the unsafe region with high strain intensity rates. However, the segmentation image will not be shown in the real-time simulation.

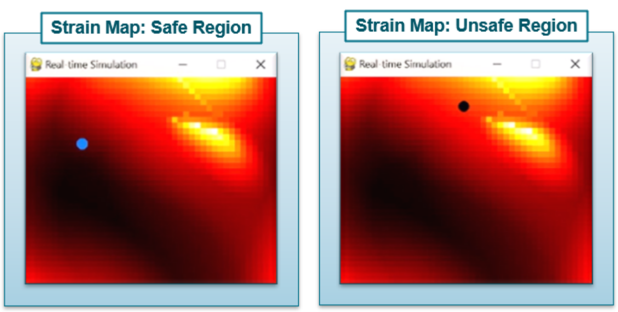

Fig. 6. Visualisation of safe region(blue dot) and unsafe region(black dot).

In the real-time simulation, a dot will represent the planar elevation and the shoulder elevation in the x and y-axis of the strain map simulation. If the dot enters the unsafe region, it will become black and if it is in the safe region, it will stay blue(figure 6).

C. Visual Feedback

With the measured shoulder angles, and defined safe and unsafe regions, visual and vibrotactile feedback can be provided. In both the visual feedback and the vibrotactile feedback experiments, four different scenarios are defined to provide feedback. In the first case, the shoulder elevation will be higher than 90 degrees and the planar elevation will be equal to or lower than 90 degrees. In the second case, both the shoulder and planar elevation will be equal to or lower than 90 degrees. In the third case, the shoulder elevation will be equal to or lower than 90 degrees and the planar elevation will be higher than 90 degrees. Lastly, in the fourth case, both the shoulder and planar elevation will be higher than 90 degrees. In the case of visual feedback, if the human enters the first scenario and the unsafe region, the pygame simulation of the strain maps will show a yellow figure with the recommended motion to move out of the unsafe region. In the second case, it will show a red figure, a green figure for the third case, and a blue figure for the fourth case. Both these figures can be observed in figure 7 and will only be displayed if they are in the unsafe region for their given configuration, otherwise, it will display the strain map with a blue dot(figure 7).

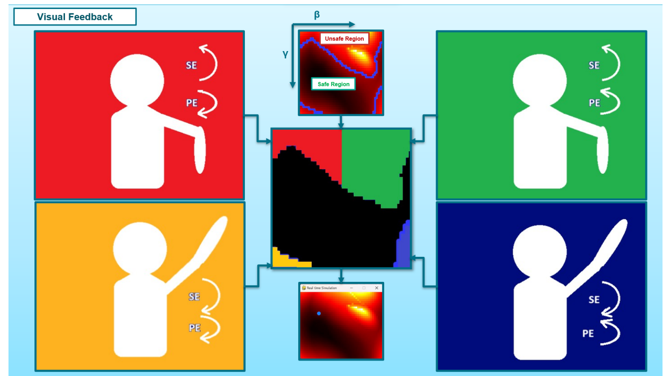

Fig. 7. Process of providing visual feedback depending on the configuration of the shoulder angles of the patient.

D. Vibrotactile Feedback

As earlier mentioned, in the experimental setup with the vibrotactile device, the same scenarios are used as in the visual feedback. However, in the case of the vibrotactile feedback setup, voice coil actuators will be used to generate feedback instead of the generated images for visual feedback. Although, to generate the vibrations with the voice coil actuators more hardware is needed. In total, the following hardware components are used to build the haptic device and can also be seen in figure 8 and 9:

- 4 Voice Coil Actuators(Tectonic TEAX14C02-8 Haptic Feedback Transducer)
- 1 Arduino Uno
- 1 Breadboard
- 1 Adafruit TCA9548A I2C Multiplexer
- 4 Adafruit DRV2605L Haptic Motor Controller
- 22 Jumpwires
- 8 long soft wires(approx. 1.6m)
- Additional Power Supply(optional)

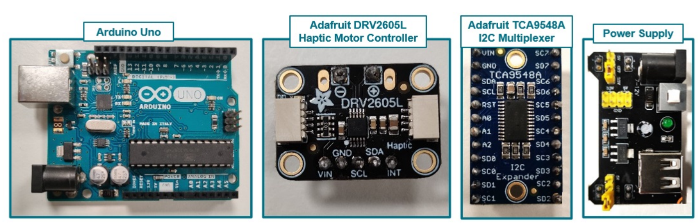

Fig. 8. Hardware components used on the breadboard.

At first, a microcontroller is needed to control the hardware components with code. In this study, Arduino Uno is used as a microcontroller with Python and Arduino code(connected with PySerial) to control the vibrations of the voice coil actuators. However, to control the haptic vibrotactile signals of each voice coil actuator, haptic motor controllers are used. In this study, the Adafruit DRV2605L Haptic Motor Controllers are used. These haptic motor controllers allow the voice coil actuators to be controlled in various ways. It has 123 built-in haptic signals in the Arduino Adafruit DRV2605 Library and this library can also be used to give vibration based on music/audio input[29]. However, every intensity level of the haptic vibration sent by each haptic motor controller is controlled by an Inter-Integrated Circuit(I2C) interface[30]. In this communication interface, two serial protocols are used(SDA(Serial Data Line), and SCL(Serial Clock Line)) to send and control the amplitude values from the Arduino Uno to the haptic motor controller[31]. Although, the Arduino Uno only has one SDA(A4) and SCL(A5) pin[32]. Due to that, one Adafruit TCA9548A I2C Multiplexer together with the Arduino TCA9548A Library is used to control all four haptic motor controllers with one Arduino. The TCA9548A I2C Multiplexer has 8 SDA and SCL pins from pin number 0 to 7 in order to provide I2C connections to other hardware components. However, to provide this, it needs to get a power supply and I2C connection from the Arduino Uno. Additionally, even every haptic motor controller needs a power supplier. This can either be done by connecting the 3.3V or 5V pin of the Arduino to the breadboard such as given in figure 9, or with the Power Supply(3.3V or 5V) given in figure 8.

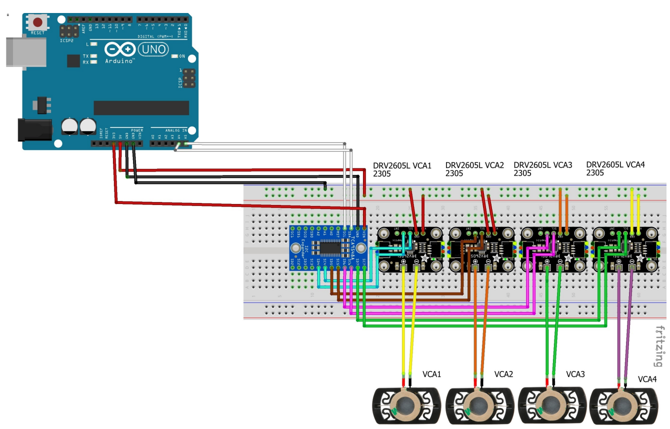

Fig. 9. Circuit wiring drawing of the haptic device without the additional power supply.

So, when every hardware component is connected to each other with wires without additional power supply, a circuit wiring diagram is obtained such as given in figure 9. The additional power supply is only needed when both the power supply of the haptic motor controller and I2C Multiplexer should be equal to 5V or 3.3V since the is only one 5V and one 3.3V pin available on the Arduino Uno. However, from figure 9, it can also be observed that the voice coil actuators are connected to the breadboard with small wires and are lying on the ground, but in reality, these voice coil actuators are connected with long wires(approx. 1.6 m) and placed on a wearable shoulder armband, which is given in the orange sections figure 10. On this wearable haptic device, the voice

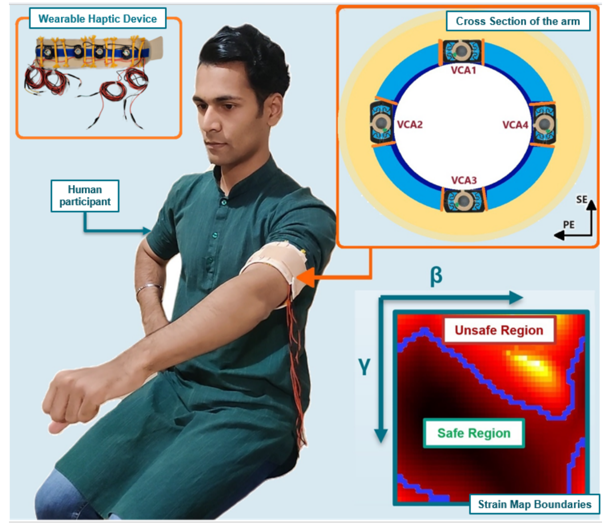

Fig. 10. The wearable haptic device and cross-section drawing with a human participant.

coil actuators are connected with hoop & loop fasteners and can be placed in different locations on the shoulder armband. Additionally, the wires are safely ordered within the haptic device such that they do not disturb the human operator while performing the experiments. This is done by stapling laces on the shoulder armband and stitching the wires within the tunnels created in the laces such as given in figure 10.

Fig. 11. Process of providing vibrotactile feedback depending on the configuration of the shoulder angles of the patient.

The goal of this setup is to create a wearable haptic device such that it can be wrapped on the upper arm and can provide vibrotactile feedback in the same four given scenarios as in the visual feedback. To do this, one voice coil actuator is placed on the right part of the arm(VCA2), one on the left(VCA4), one on the upper part(VCA1), and one on the lower part(VCA3) of the arm with the haptic device. So, if the human is entering in the first case, VCA1 and VCA4 will vibrate to decrease shoulder elevation and increase planar elevation. In the second case, VCA3 and VCA4 will vibrate to increase both shoulder elevation and planar elevation. In the third case, VCA2 and VCA3 will vibrate to increase shoulder elevation and decrease planar elevation. Lastly, in the fourth case, VCA1 and VCA2 will vibrate to both decrease the shoulder elevation and planar elevation. Additionally, these vibrations will only occur if and only if the human is entering the unsafe region(figure 11). Otherwise, no vibrotactile feedback will be provided(figure 11). So, when all the processes of human pose estimation(figure 4), image segmentation(figure 5), visual feedback(figure 7), and vibrotactile feedback(figure 11) are combined, then the total feedback mechanism process can be sketched such as given in figure 12.

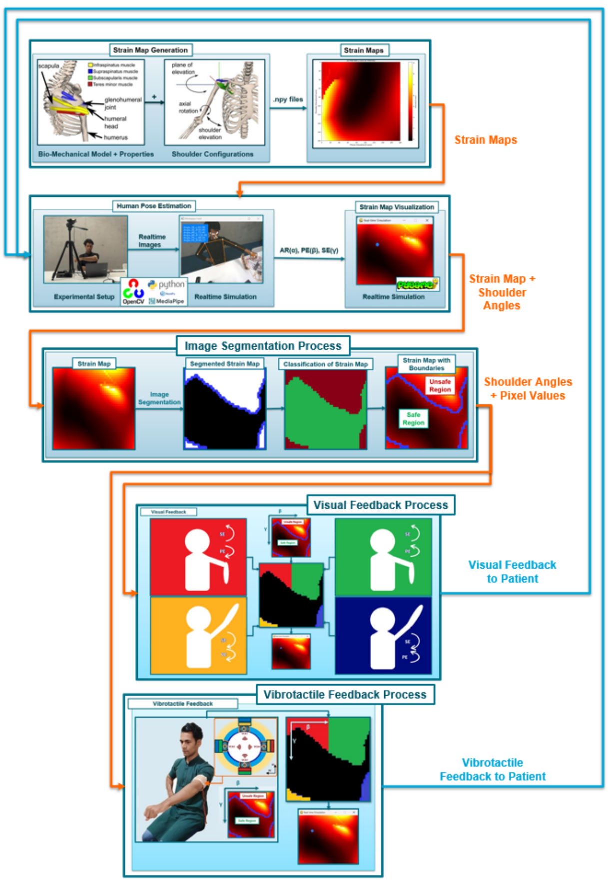

Fig. 12. Total feedback mechanism process with strain maps + Vibrotactile/Visual Feedback.

III. Results

Unfortunately, the axial rotation angle measurements are imprecise, which results in an inaccurate representation of the strain maps. Additionally, the planar elevation angle is also partially incorrect when the camera is placed in front of the human. However, when the camera is placed upside-down the human, the planar elevation angle is more accurate. Nonetheless, this change will compromise the shoulder elevation's angle precision. To solve these problems, the initial experimental setup is changed and experiments are divided into the following three parts:

- Experimental Setup 1: Testing both planar and shoulder elevation together with a constant axial rotation angle.
- Experimental Setup 2: Testing individually planar elevation with camera upside-down.
- Experimental Setup 3: Testing individually shoulder elevation with the camera in front of the human with a constant axial rotation angle.

The first experimental setup will have almost the same setup as described in the methodology. The only difference will be that the axial rotation angle will not change, which leads to a static strain map. However, the second and third experiments will have more changes. In these cases, the visual feedback will display different figures compared to the initial figures given in figure 7. Besides that, the vibrotactile feedback will also be provided in different places compared to the initial setup. In the case of only testing planar elevation, a purple figure will be displayed when the planar elevation is low and a pink figure will be displayed when it is too high in case of visual feedback(figure 13).

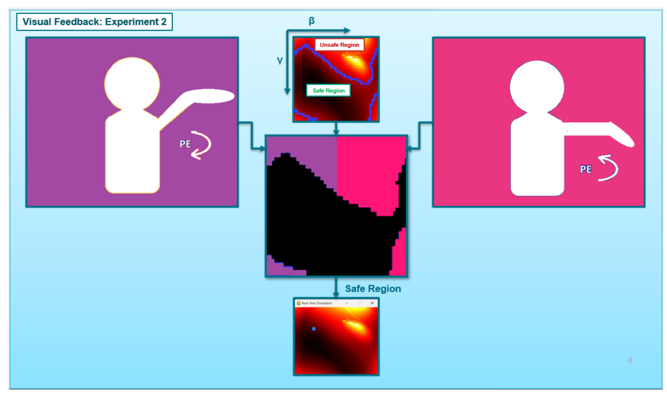

Fig. 13. Visual Feedback for Planar Elevation in Experiment 2.

For vibrotactile feedback, VCA4 will vibrate if the planar elevation angle is too low and VCA2 will vibrate if it is too high(figure 15). In the case of only testing the shoulder elevation, a dark-green figure will be displayed when the shoulder elevation angle is too low and an orange figure will be displayed if the shoulder elevation is too low(figure 14). For vibrotactile feedback, VCA3 will vibrate if the shoulder elevation angle is too low and VCA1 will vibrate if it is too high(figure 15).

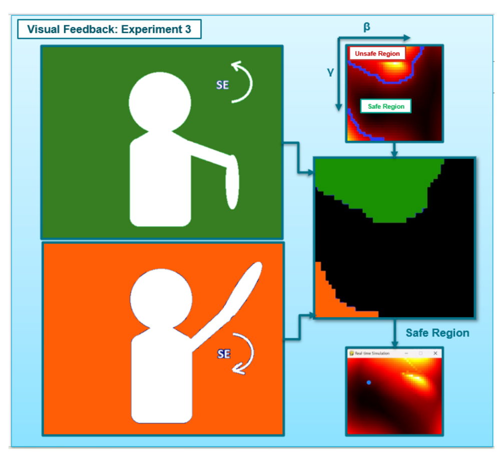

Fig. 14. Visual Feedback for Shoulder Elevation.

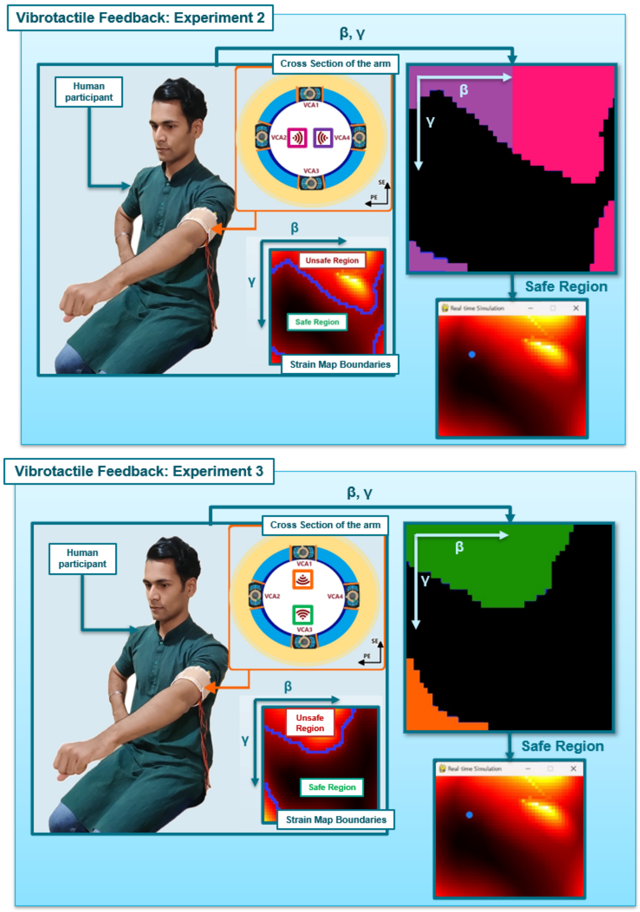

Fig. 15. Vibrotactile Feedback for planar elevation and shoulder elevation individually.

A. Experiment 1: Planar & Shoulder Elevation

In this experiment, the axial rotation is kept at 44 degrees and the camera in front of the human is slightly tilted to improve the measurement of the planar elevation angle, such as given in figure 16.

Fig. 16. Camera Setup for experiment 1(left), experiment 2 Planar Elevation(middle), and experiment 2 Shoulder Elevation.

In this case, the experiment is conducted with the same strain map boundary methods as given in figure 7 and 11, and the results of it can be observed in figure 17 for visual feedback and figure 18 for vibrotactile feedback.

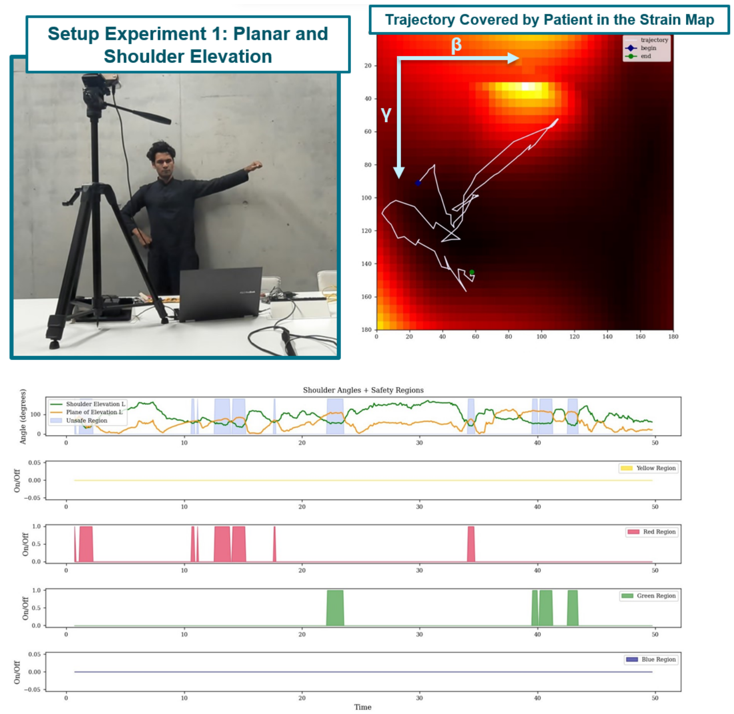

Fig. 17. Trajectory covered by the user while using Visual Feedback and the time covered in different unsafe regions while doing planar & shoulder elevation exercises.

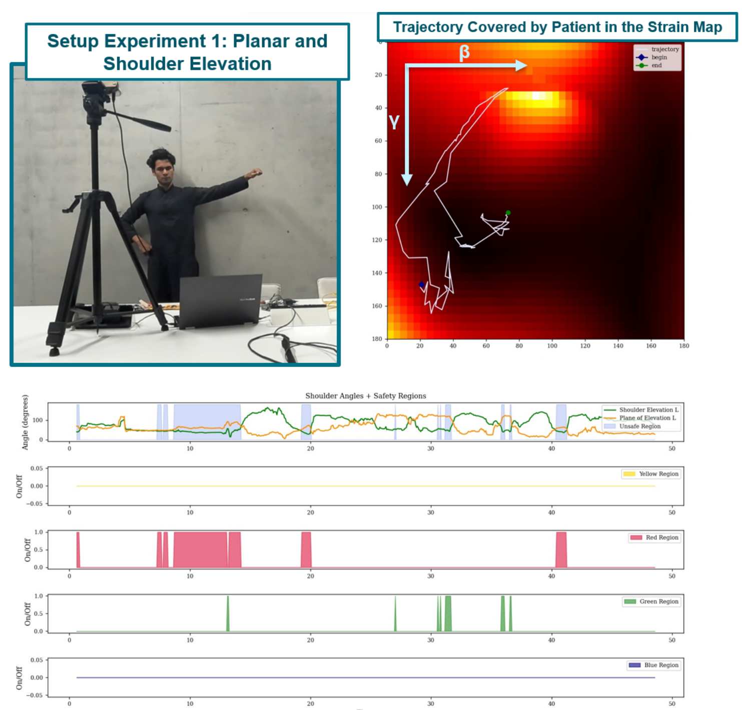

Fig. 18. Trajectory covered by the user while using Vibrotactile Feedback and the time covered in different unsafe regions while doing planar & shoulder elevation exercises.

In both cases, the user only could reach red and green unsafe regions while performing the experiments. This mainly happened because the positions to reach the other injuries were difficult for the user and there was still some inaccuracy in estimating the shoulder angles based on the camera setup for this experiment. Due to that, this setup needs to be improved for future work.

B. Experiment 2: Planar Elevation & Experiment 3: Shoulder Elevation

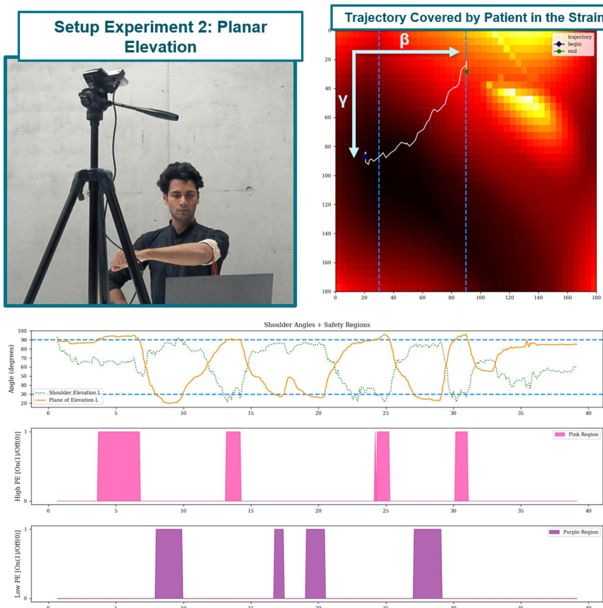

Fig. 19. Trajectory covered by the user while using Visual Feedback and the time covered in different unsafe regions while doing planar elevation exercises.

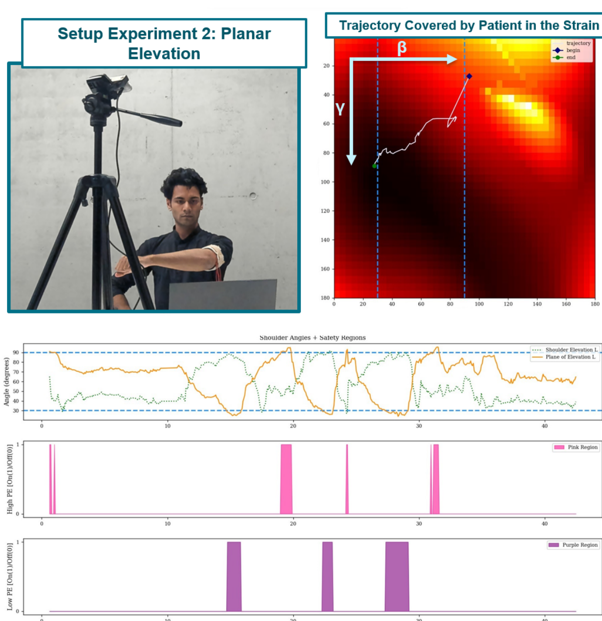

Fig. 20. Trajectory covered by the user while using Vibrotactile Feedback and the time covered in different unsafe regions while doing planar elevation exercises.

In experiment 2, the axial rotation is kept at 0 degrees(strain map in figure 19&20) and the camera is almost upside down the user to improve the measurement of the planar elevation angle. On the other hand, in experiment 3 the axial rotation is kept at 44 degrees(strain map in figure 21&22) and the camera is in front of the user to obtain accurate shoulder elevation angles. Both these experimental setups are given in figure 16, and can also be observed in the results for planar elevation in figure 19 & 20, and in the results of shoulder elevation in figure 21 & 22 respectively. Despite that, figure 19 & 20 for experiment 2 and figure 21 & 22 for experiment 3 respectively show the vibrotactile and visual feedback outcomes of the covered trajectory and time within different unsafe regions.

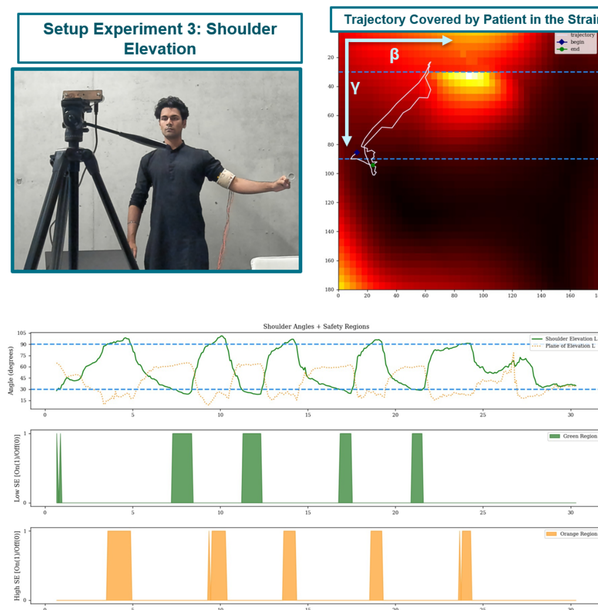

Fig. 21. Trajectory covered by the user while using Visual Feedback and the time covered in different unsafe regions while doing shoulder elevation exercises.

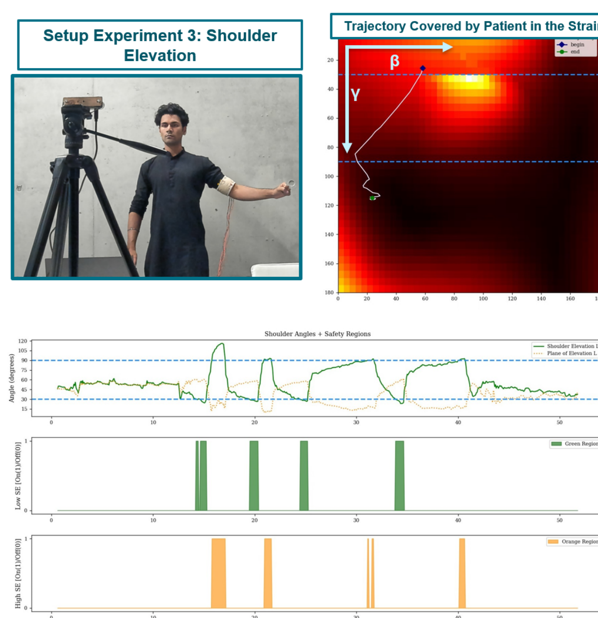

Fig. 22. Trajectory covered by the user while using Vibrotactile Feedback and the time covered in different unsafe regions while doing shoulder elevation exercises.

However, the results of experiments 2 and 3 did not use the strain map boundaries which were shown in figure 13, 14, and 15, since the user was unable to reach the unsafe region with high shoulder elevation and low planar elevation. Instead of the strain map boundaries, feedback was given in both vibrotactile and visual forms when the corresponding shoulder angle was below 30 and above 90 degrees, and the strain maps were used to check the shoulder strain intensity in each trajectory. Nevertheless, the experimental results with the strain map boundaries are provided in the appendix including the fully covered trajectories in the experiment, which also holds for the other given results in this paper.

When the experimental results of visual and vibrotactile feedback for planar elevation are compared, it can clearly be observed that in visual feedback the user is spending more time in the provided unsafe regions compared to vibrotactile feedback(figure 19 and 20). The same is also observed in figure 21 and 22 for the experimental results with shoulder elevation. In addition to that, for both experiments, the duration of each feedback time block is in most cases also slightly longer during visual feedback than vibrotactile feedback. However, the peaks of the measured shoulder elevation and planar elevation angles are sometimes higher during vibrotactile feedback than visual feedback(e.g. during the first shoulder elevation peak in figure 22). So, based on the provided results, vibrotactile feedback shows better performance compared to visual feedback. However, both have their challenges to improve for further work.

IV. Discussion

Though this study has shown that vibrotactile feedback has the potential to guide users to reduce the risk of shoulder injuries and maintain healthy postures, it is crucial to discuss the observations within this study and the remarks for future work.

A. Human Pose Estimation

As earlier observed, computed vision-based methods are used to estimate the shoulder angles and based on the obtained literature about it Mediapipe has been used for pose estimation. However, using this pose estimation library has its drawbacks. At first, estimating the axial rotation is difficult and leads to incorrect values based on the methods which were used in this study. To solve this problem for future work, a more extensive literature and experimental study should be done on computed vision-based methods to find a more optimal method to estimate shoulder angles. Additionally, there should also be investigated if human pose estimation with multiple cameras can improve the estimation of the shoulder angles. Secondly, as observed earlier in the results of experiment 1, while testing both planar elevation and shoulder elevation angles, the accuracy of both angles decreased. To solve this for future work, human pose estimation should be done with multiple cameras, since the results of experiments 2 and 3 have shown that cameras on different positions lead to improvements in the estimation of either shoulder elevation or planar elevation depending on the placed position. Lastly, though computed vision-based methods are in most cases less expensive compared to wearable-based methods for human pose estimation, more investigation should be done to find less expensive wearable-based methods and to find possibilities to combine wearable-based methods with computed vision-based methods to find the optimal setup to estimate the shoulder angles of the human, while keeping the costs low.

B. Strain Maps

Though strain maps provide an intuitive representation of the RC tendon strain, it has limitations. If one of the shoulder angles is measured inaccurately, it will affect the accuracy of the strain map and will lead to providing inaccurate feedback to the patient. Additionally, in both [1] and [10] the strain maps were used when the patients did not apply muscle activation during the experiments. Due to that, the actual strain intensity within this study is higher than displayed within the designed feedback process. So, for future work, the strain maps should be adapted to provide more accurate feedback.

C. Visual and Vibrotactile Feedback

As earlier observed, the vibrotactile feedback was performing better compared to visual feedback. However, both need to be improved for future work. In the visual feedback, it was not able to display the feedback figure continuously. This makes it sometimes hard to perceive and react fast to the provided visual feedback. Due to that, this should be improved for future work. In the case of vibrotactile feedback, in most cases it provided feedback. However, sometimes one voice coil actuator does not vibrate, since the Arduino and Python code are separated and connected via PySerial, which makes the connection between the Python code and the hardware more unstable. To improve this, more extensive literature should be done on which microcontroller should be used to obtain optimal vibrotactile feedback and learn its programming language for future work. At this moment, this study recommends using a Raspberry Pi instead of Arduino, since Raspberry Pi can control the hardware within Python, which makes the connection more stable[33]. Lastly, after these improvements, both vibrotactile and visual feedback need to be tested on a group of human participants to get a better view of how both of these types of feedback can be improved in the future.

D. Costs and Production

As earlier mentioned, the following components were used to make the wearable haptic device for providing vibrotactile feedback:

- 4 Voice Coil Actuators(Tectonic TEAX14C02-8 Haptic Feedback Transducer) (14.41 EUR)
- 1 Arduino Uno (24.95 EUR)
- 1 Breadboard (6.95 EUR)
- 1 Adafruit TCA9548A I2C Multiplexer (8.25 EUR)
- 4 Adafruit DRV2605L Haptic Motor Controller (38.00 EUR)
- 22 Jumpwires (2.95 EUR)
- 8 long soft wires(approx. 1.6m) (5.90 EUR)

- Additional Power Supply(optional) (15.20 EUR)

When the costs of all these components are combined, the total cost would be equal to 116.61 EUR(29830 PKR) with the additional power supply and 101.41 EUR(32092 PKR) without the additional power supply. Though these values are almost equal to the average income of a Pakistani farmer, mass producing and buying the component within the country in which the rural areas are places will lead to a decrease in the costs and a small number of jobs within that country[34]. However, in this cost analysis, the cover of the wearable haptic device is not considered, since the design needs to be made more user-friendly and suitable for large-scale production for future work.

V. Conclusion

In this study, novelty is shown by investigating the potential of pairing vibrotactile feedback with strain maps of the shoulder muscles to guide users to maintain healthy postures and reduce risks of shoulder injuries within rural areas. To provide feedback with strain maps, the shoulder angles have been determined with OpenCV and MediaPipe libraries in Python. To display the strain maps, PyGame and OpenCV were used to draw the boundaries between high and low-strain regions within the shoulder. Visual feedback was provided within the strain map display and vibrotactile feedback was provided with a wearable haptic device. Unfortunately, the axial rotation was inaccurate and the accuracy of the other shoulder angles depended on the position of the camera. Due to that, user experiments were executed for shoulder elevation and planar elevation individually. The results observations by the user have shown that vibrotactile feedback has a genuine potential to guide users in rural areas to reduce the risk of shoulder injuries and maintain healthy postures with and without strain maps. However, both strain maps and vibrotactile feedback have their drawbacks which should be improved for future work.

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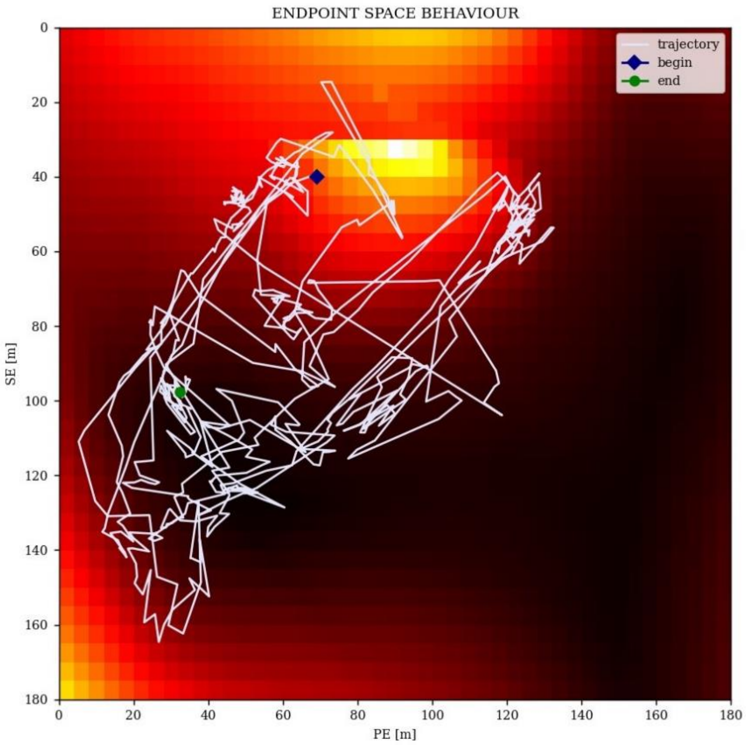
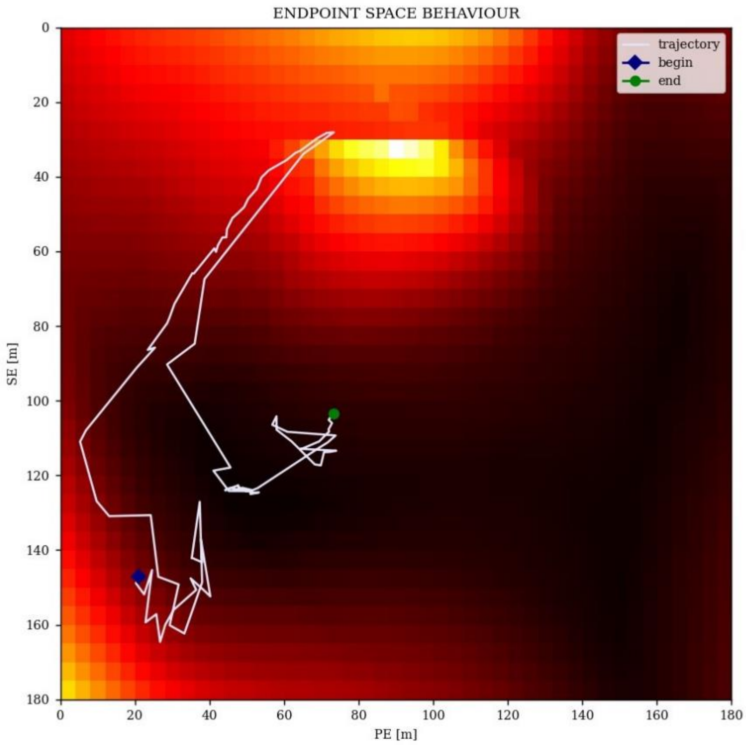
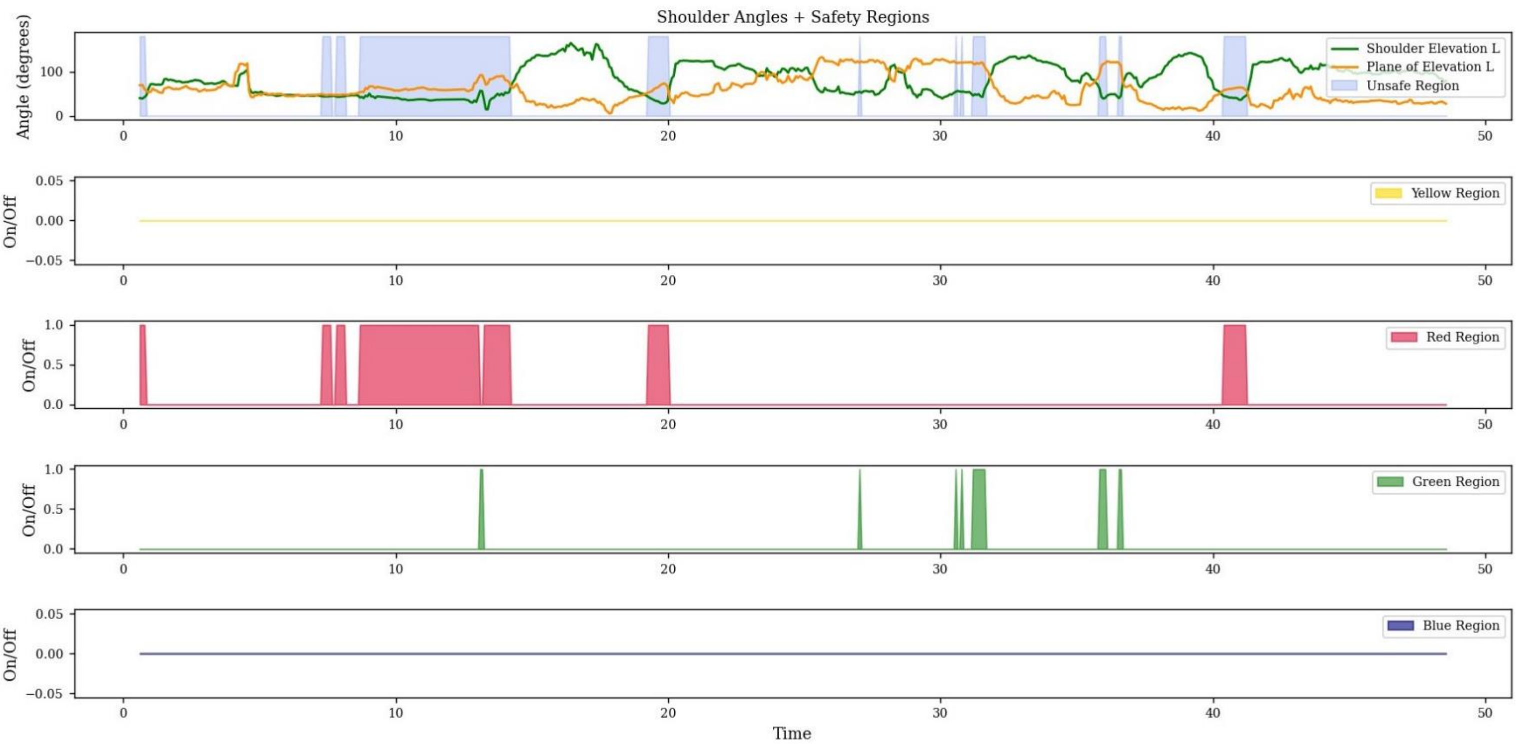
Table of Contents of Appendix

Appendix A: Raw Experimental Data Results

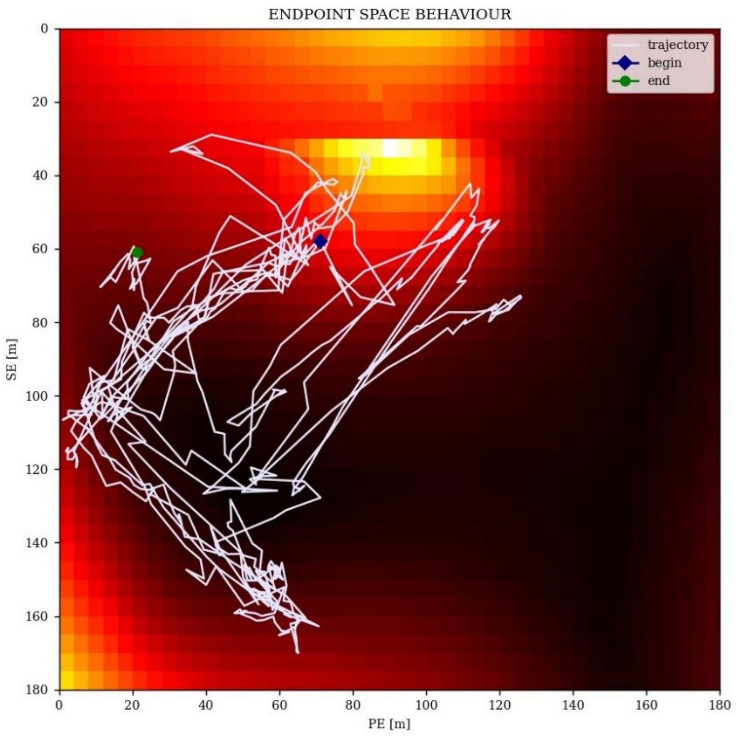
Experiment 1: Vibrotactile Feedback

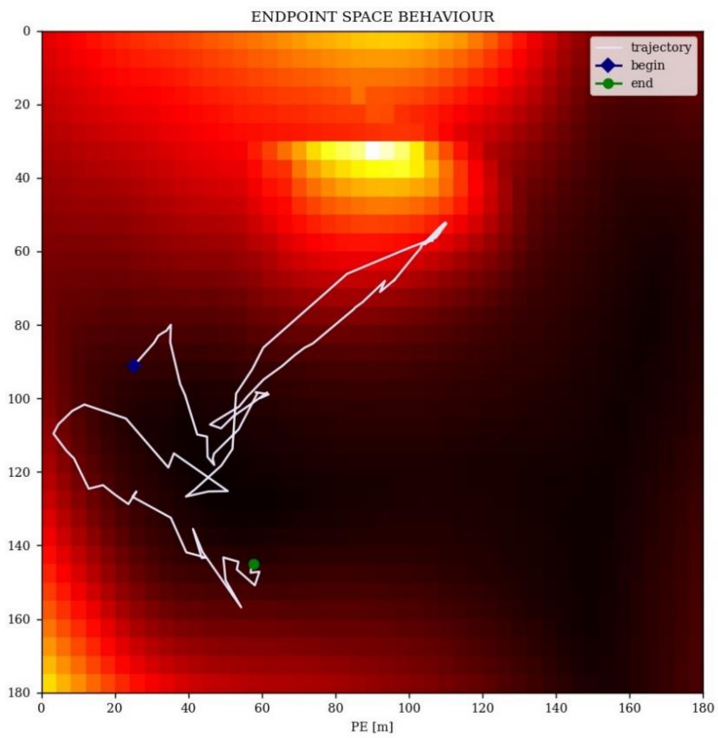


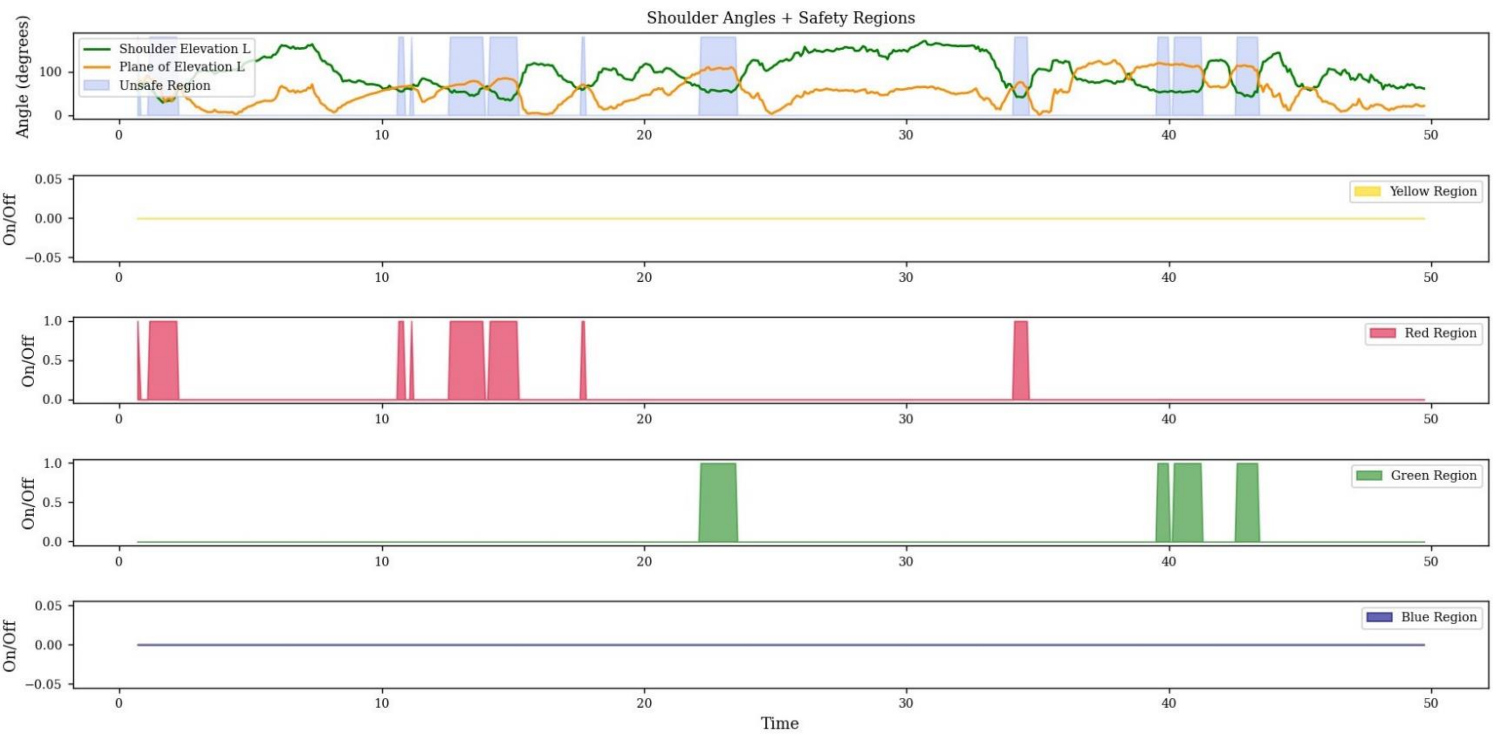




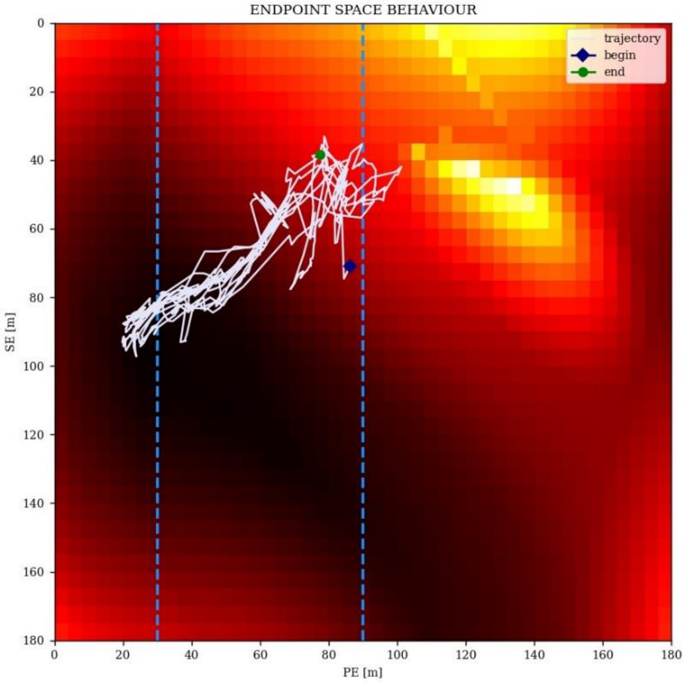
Experiment 1: Visual Feedback

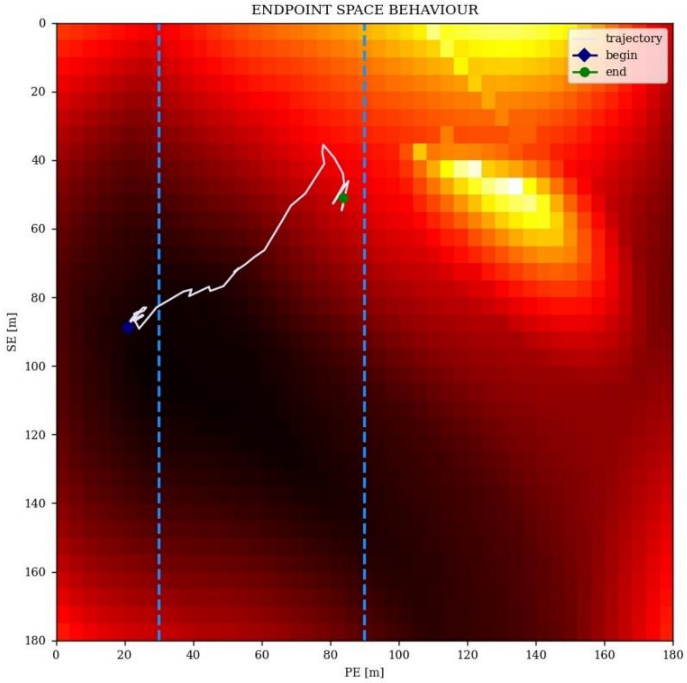


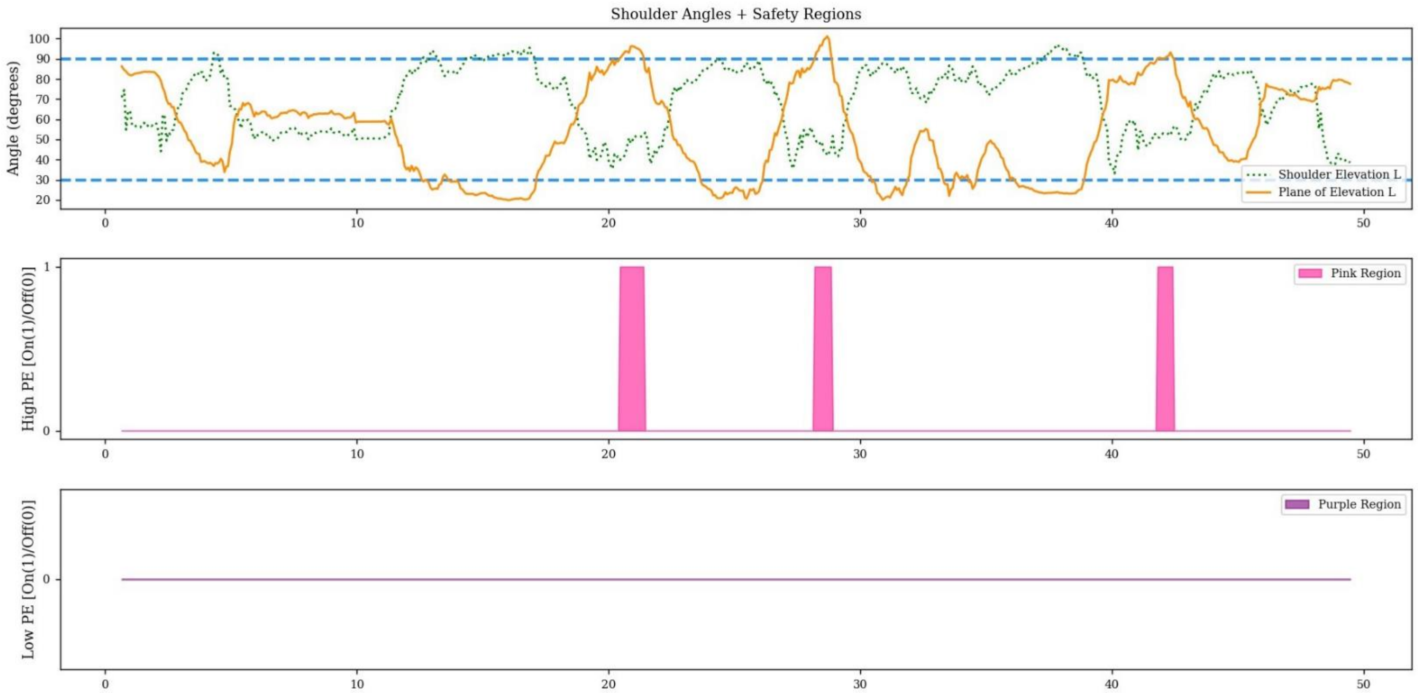




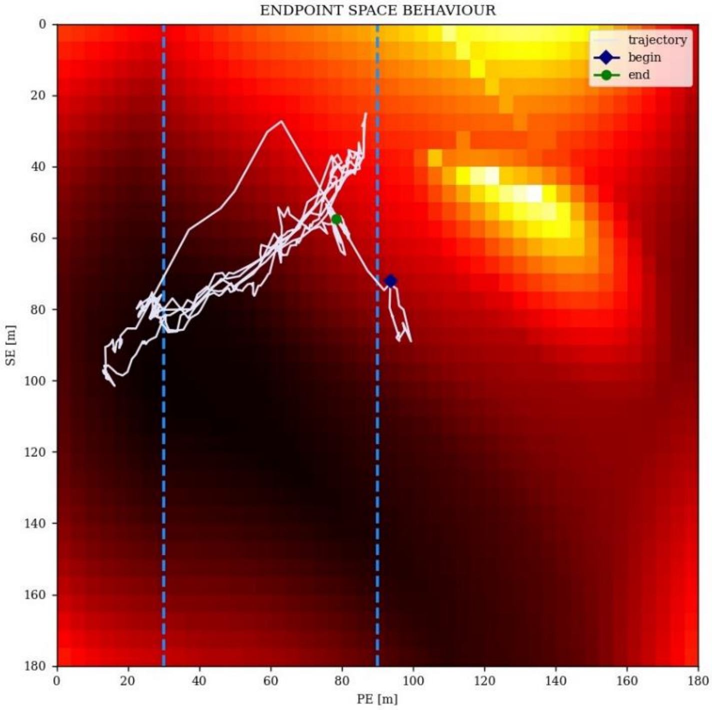
Experiment 2 Planar Elevation: Vibrotactile Feedback(incl. Strain Conditions)

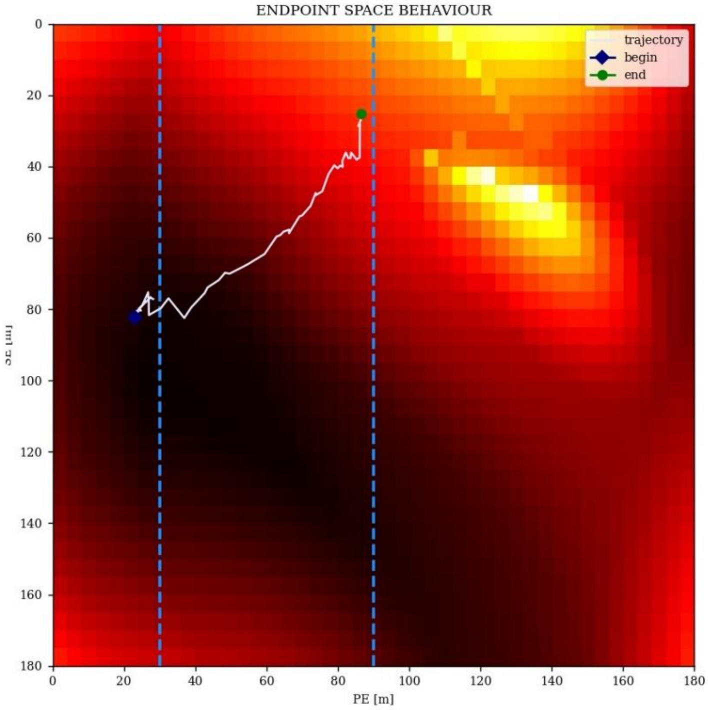


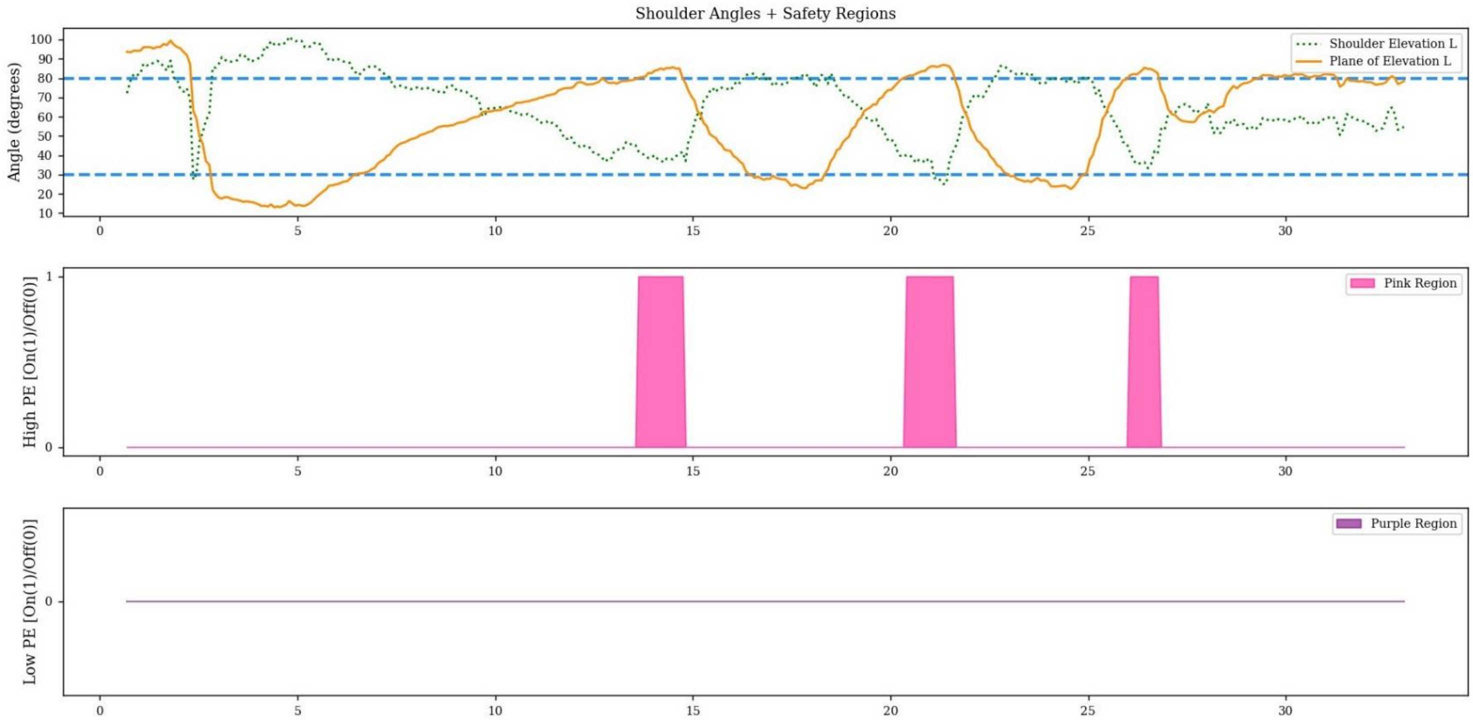




Experiment 2 Planar Elevation: Visual Feedback(incl. Strain Conditions)







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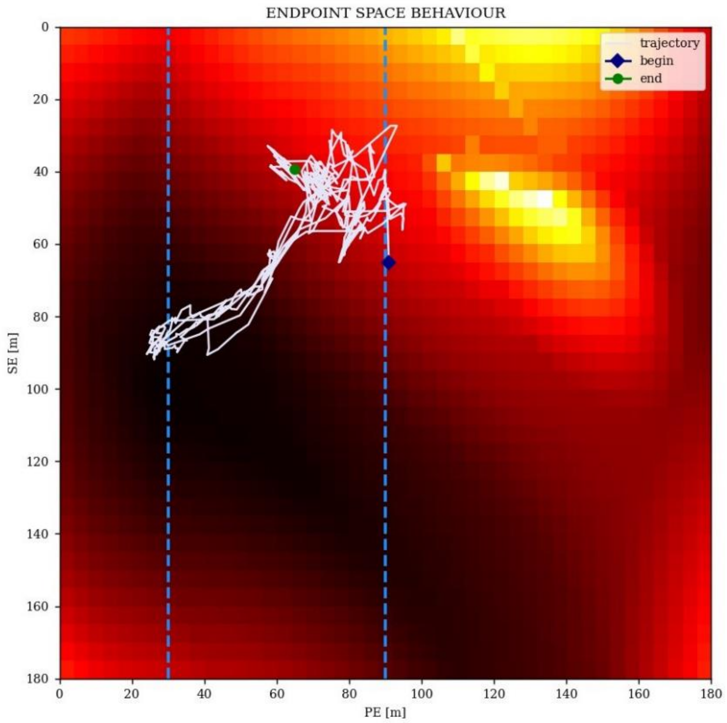
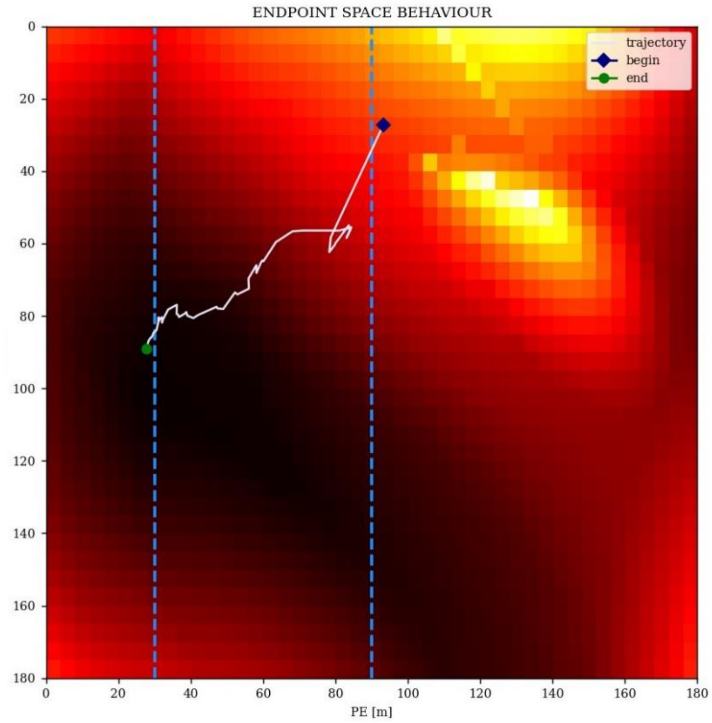
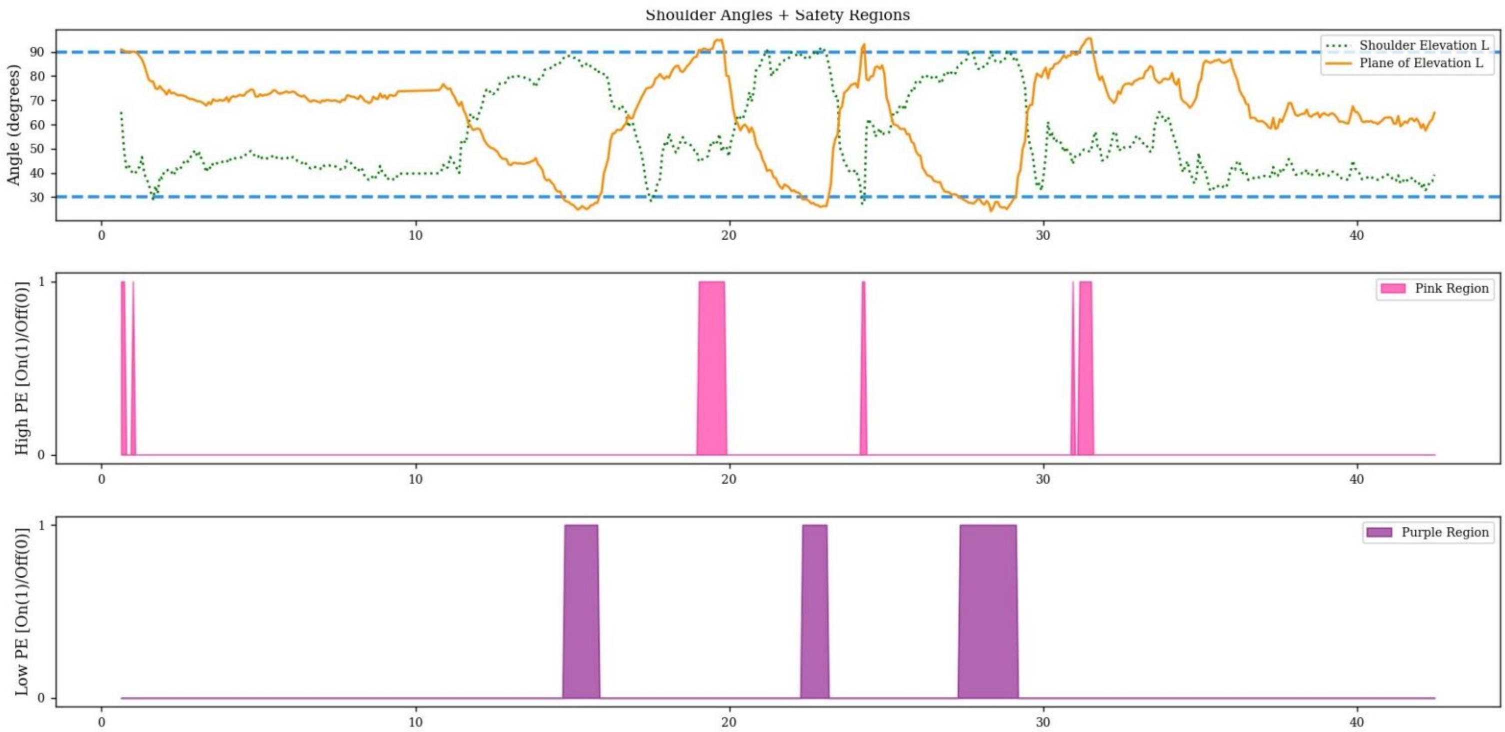
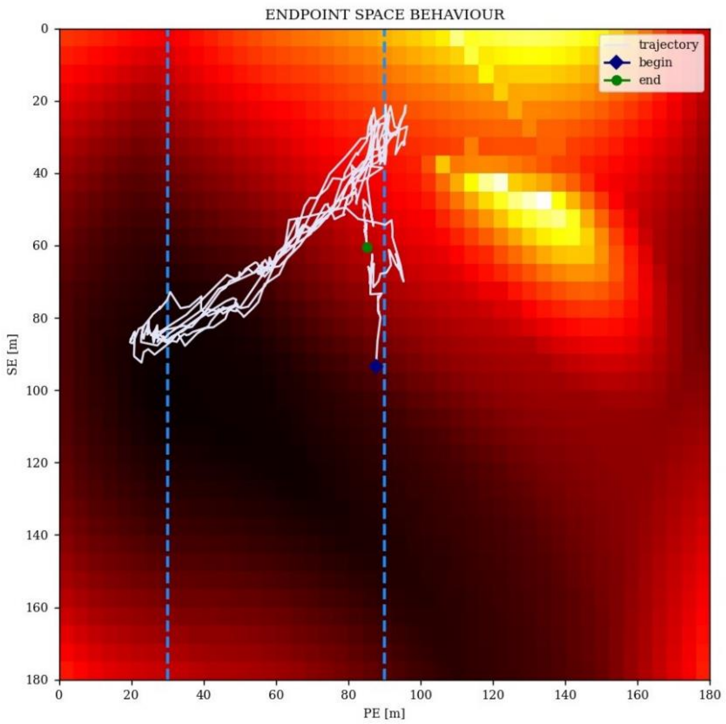
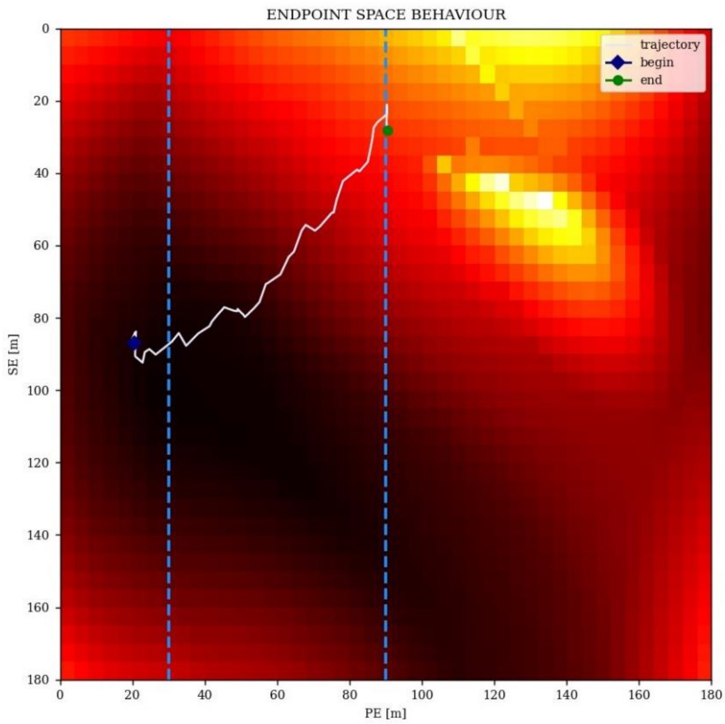


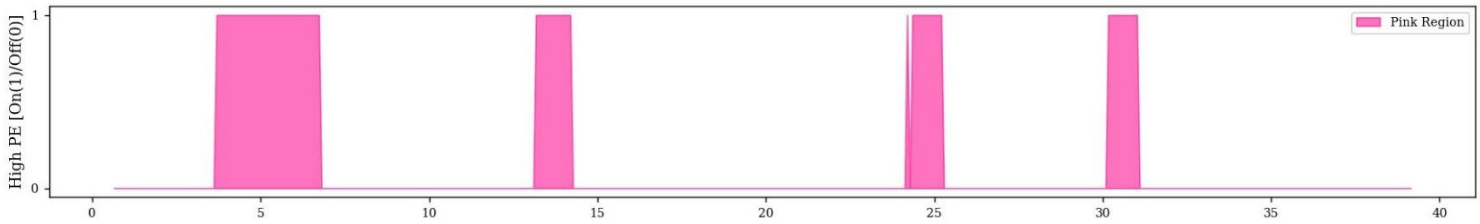


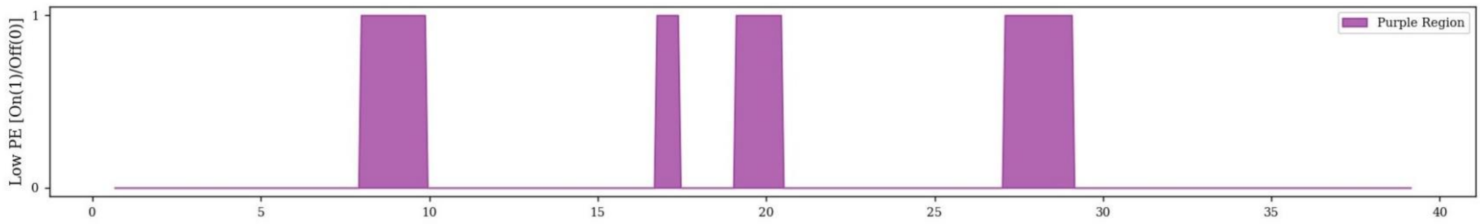


Experiment 2 Planar Elevation: Visual Feedback

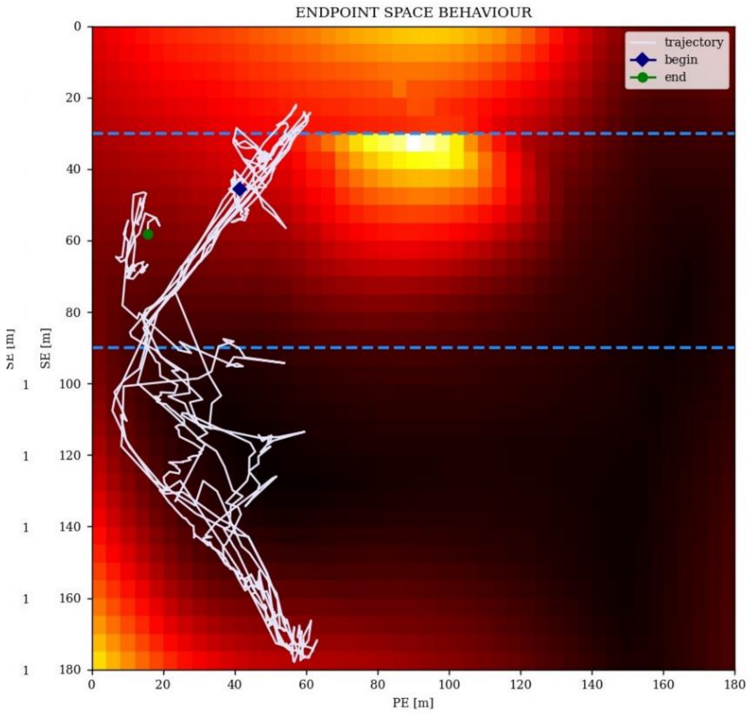


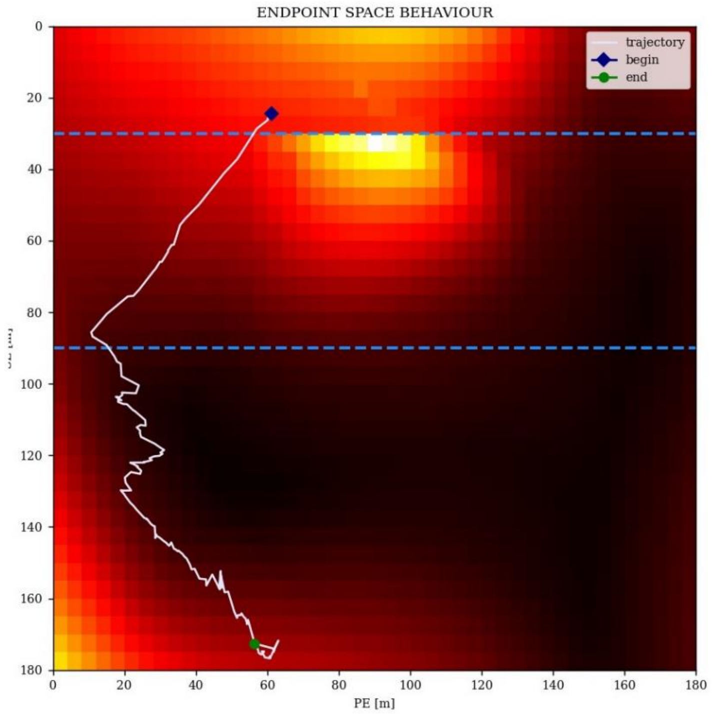


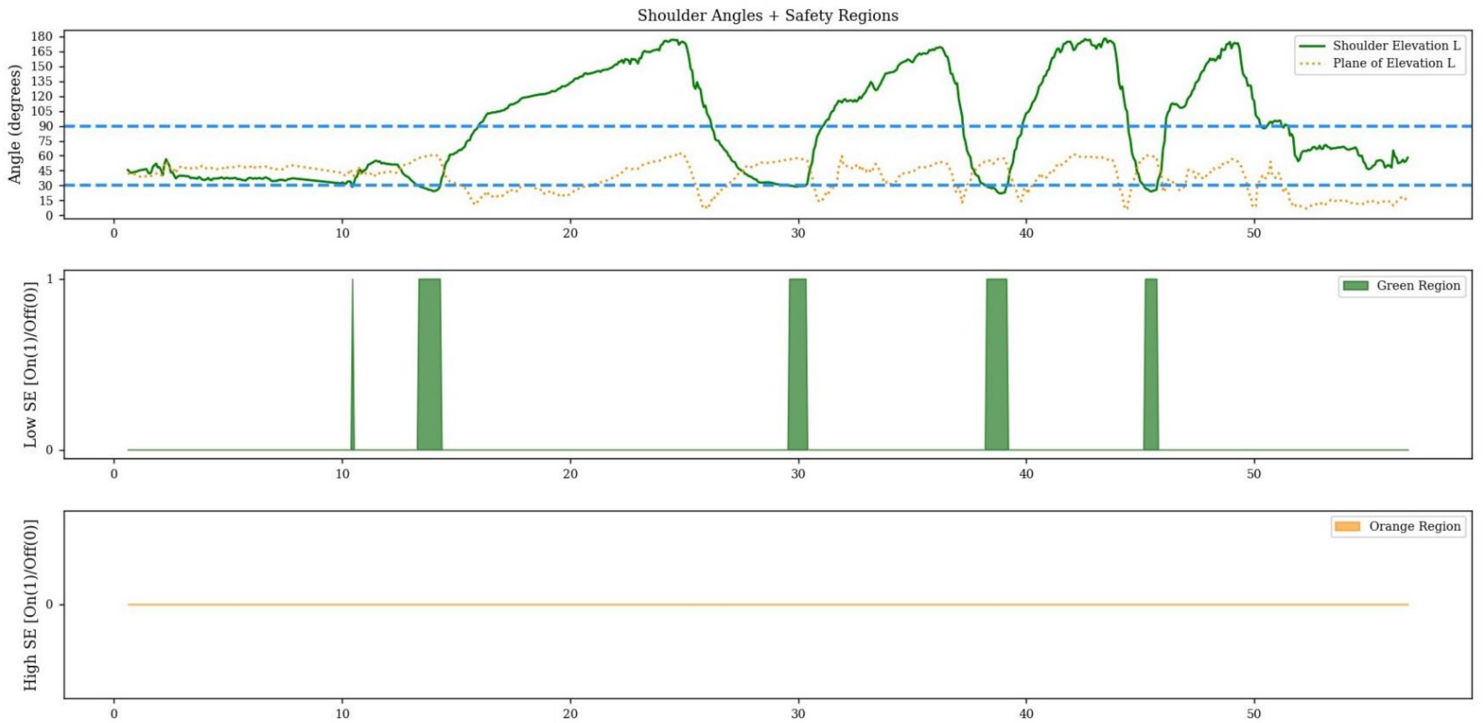




Experiment 2 Shoulder Elevation: Vibrotactile Feedback(incl. Strain Conditions)







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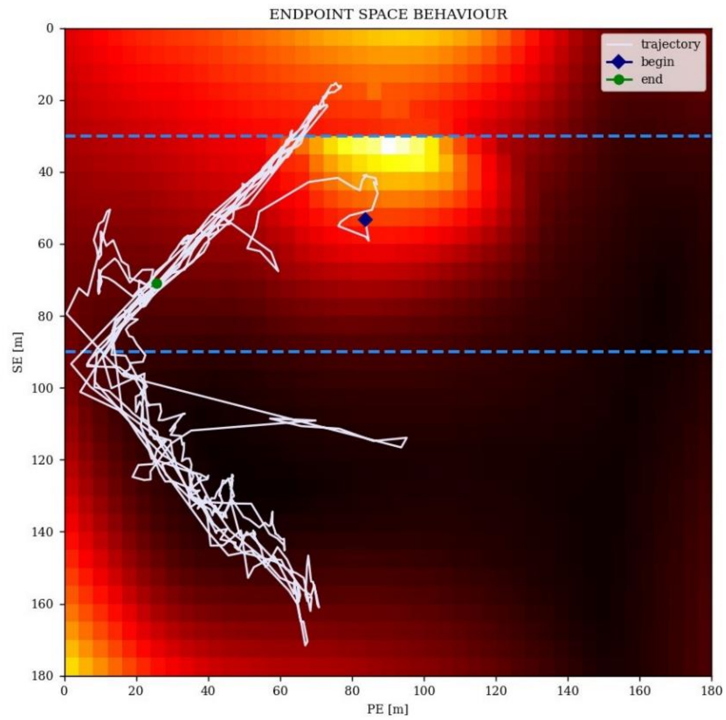
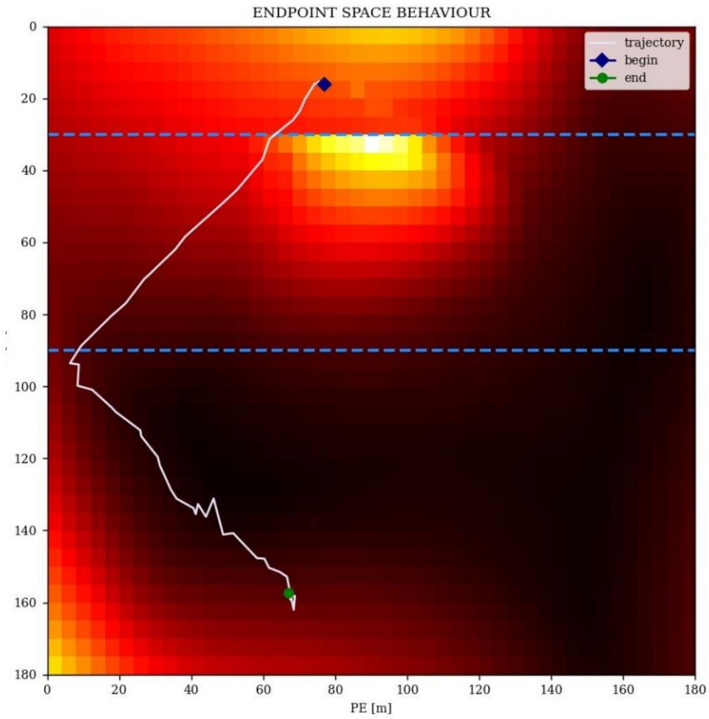
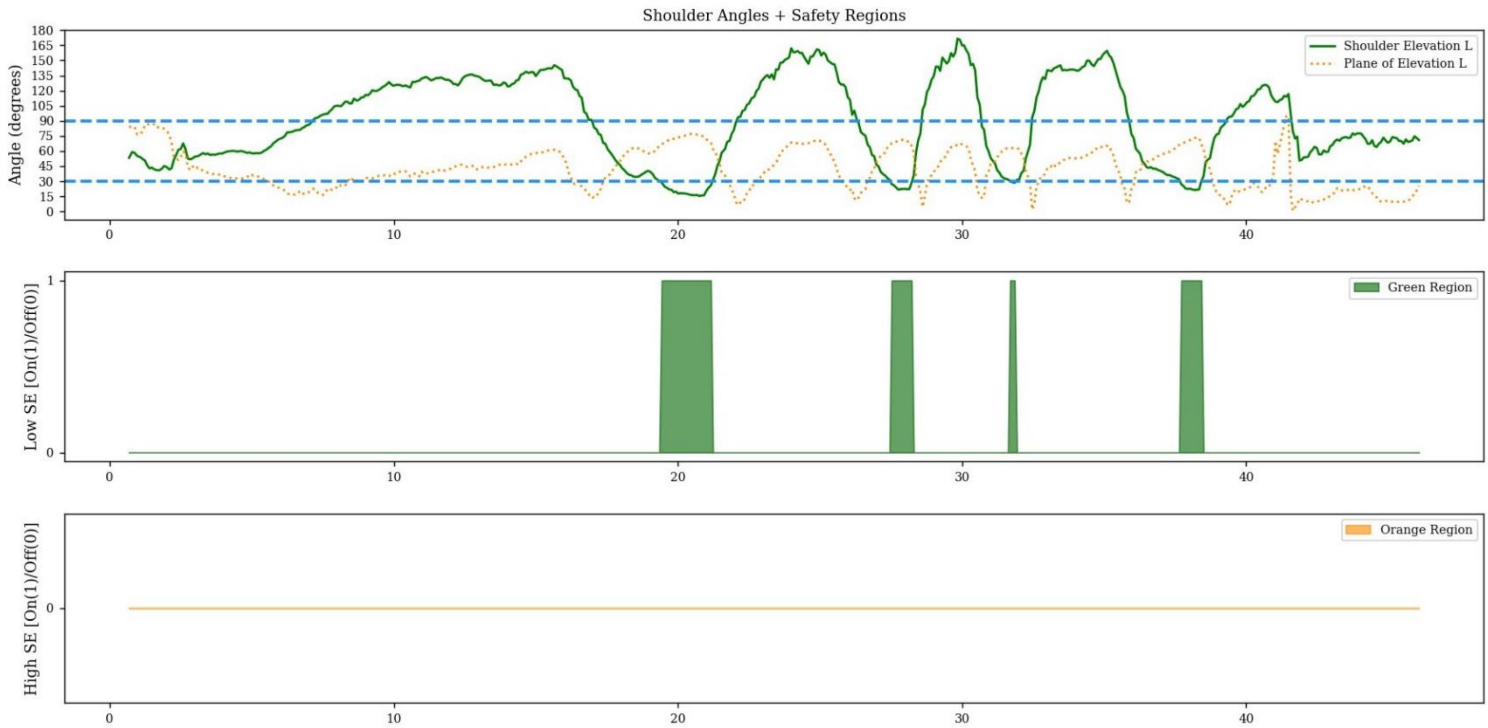
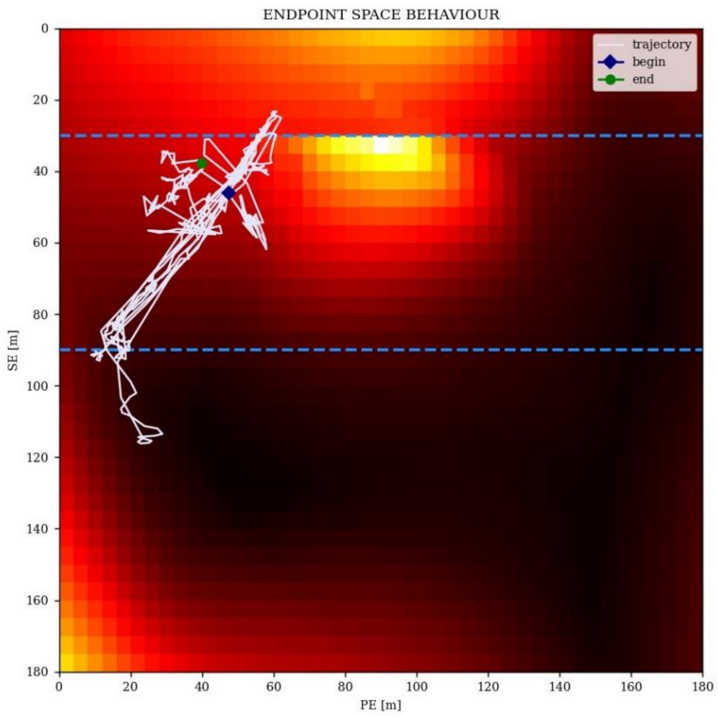
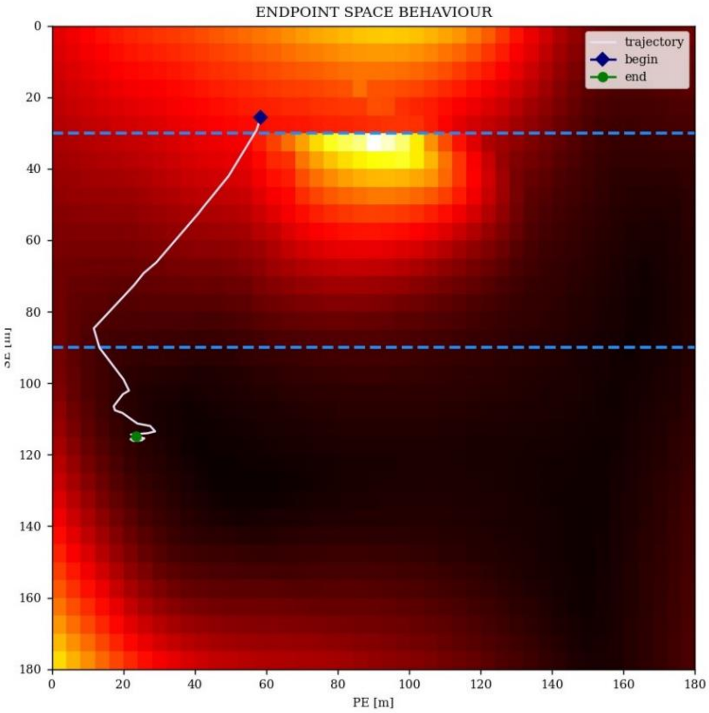


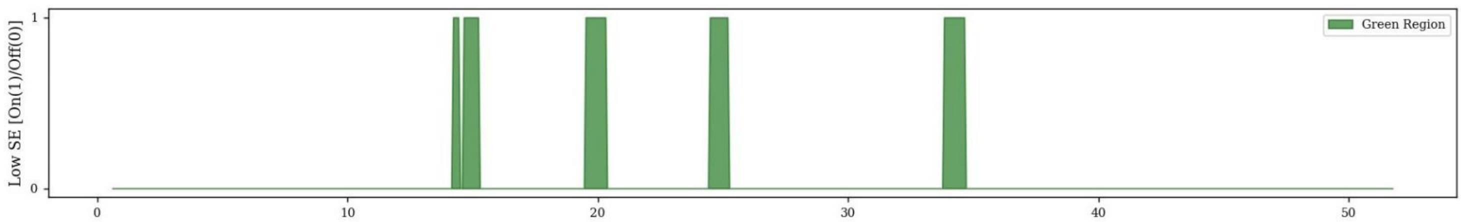


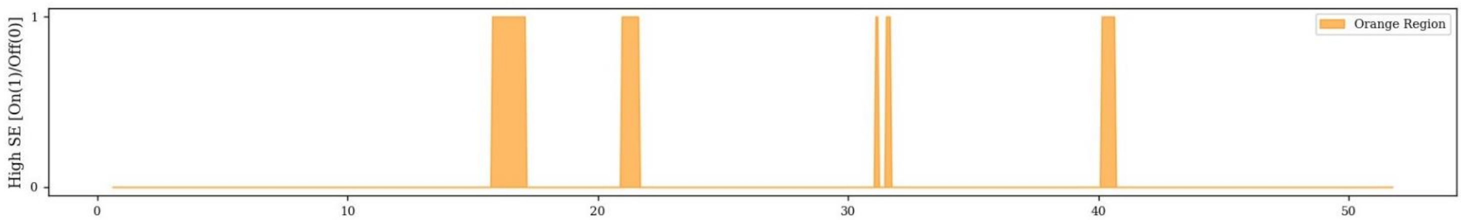


Experiment 2 Shoulder Elevation: Vibrotactile Feedback

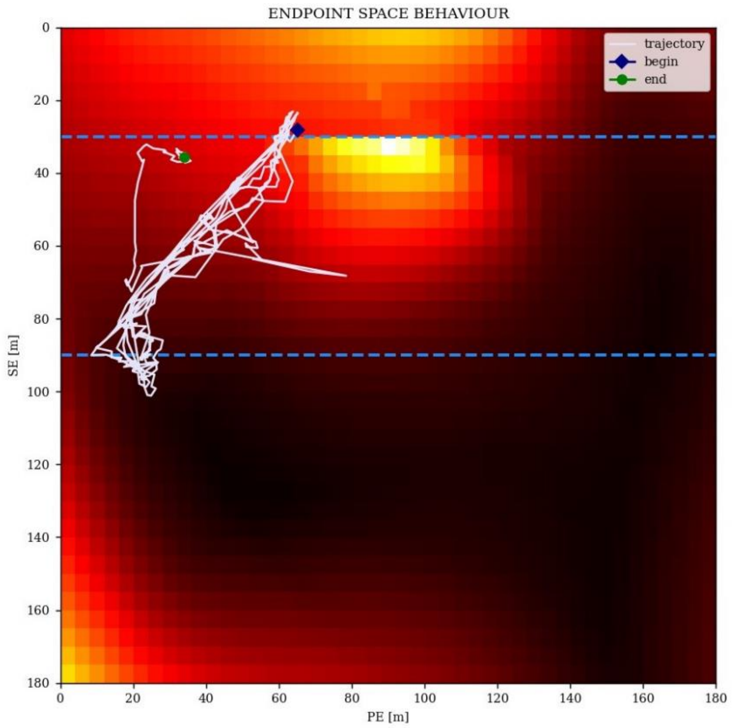


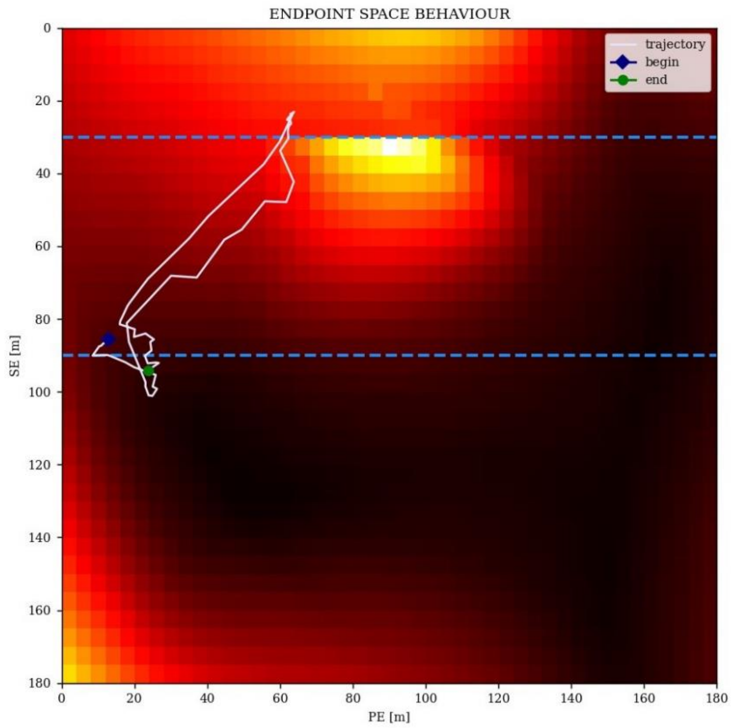


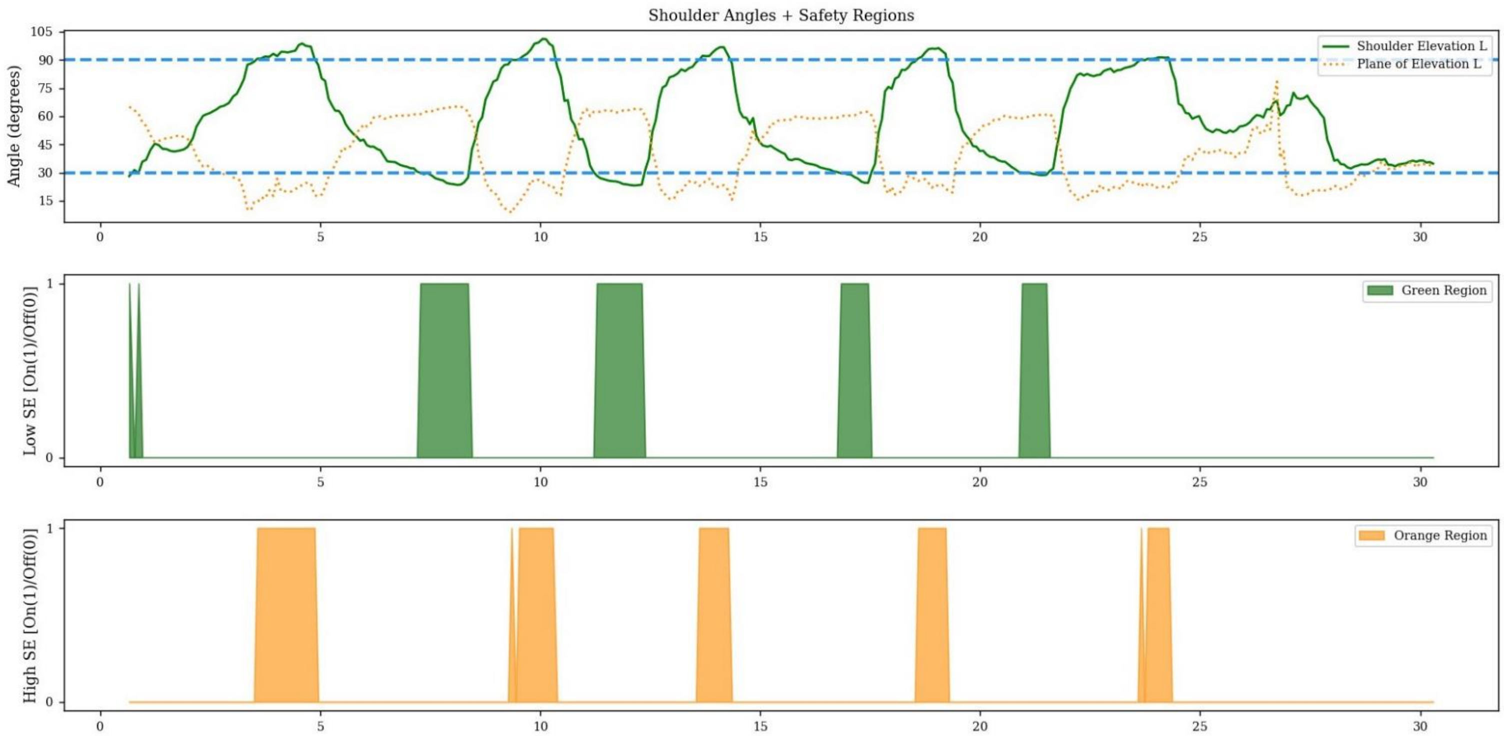




Experiment 2 Shoulder Elevation: Visual Feedback







Appendix B: Electrical Scheme

Electric Scheme of Haptic Device