Fatigue-Adaptive Game to Protect the Infraspinatus and Supraspinatus from Overuse During Robot-Assisted Shoulder Rehabilitation

by

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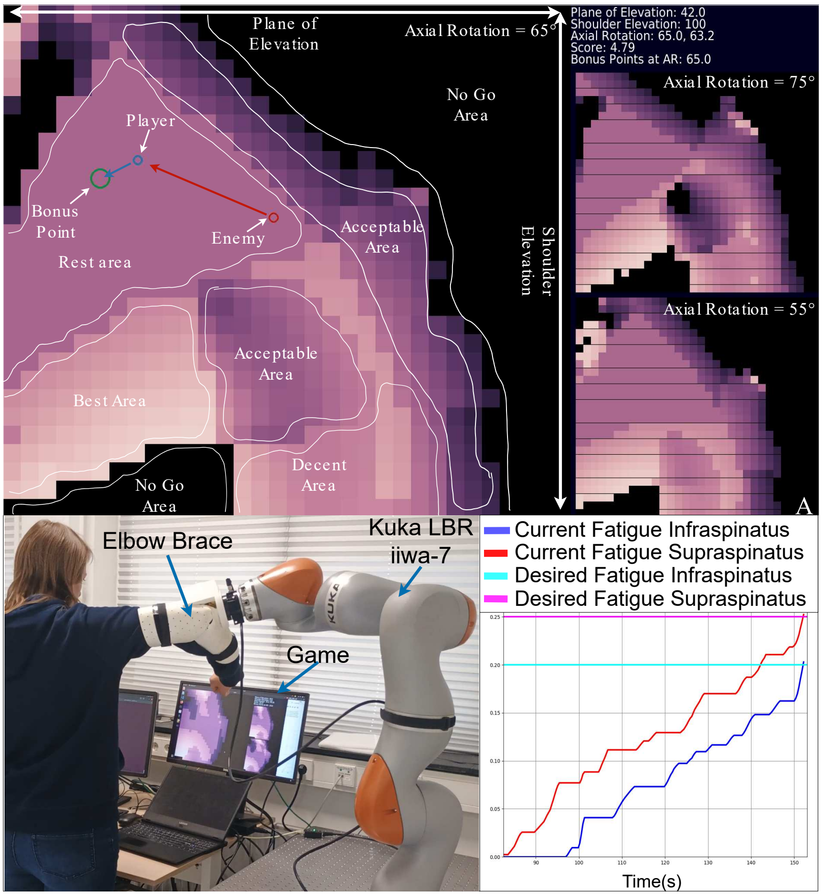
Master Thesis



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Fatigue-Adaptive Game to Protect the Infraspinatus and Supraspinatus from Overuse During Robot-Assisted Shoulder Rehabilitation

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***Abstract*—With a growing elderly population, shoulder injuries are becoming more common, and part of the recovery plan is to go to physiotherapy. However, to alleviate the demand for physiotherapists, robots could help with shoulder rehabilitation. To do this safely and enjoyably, the robot will need to prevent re-injury caused by fatigue while keeping the patient interested and motivated to continue with their therapy. In this study, a method for managing fatigue of the two most commonly injured shoulder muscles, the supraspinatus and infraspinatus, in a game is proposed and tested. To validate the developed method, a human factors experiment was conducted. The fatigue-adaptive game was compared to a baseline in which participants controlled fatigue themselves. The participants played three cases for each version of the game. To minimize the risk of over-fatiguing during physiotherapy and not crossing the line of being too fatigued. Therefore, we measured the overshoot of fatigue in both versions of the game. The mean of the overshoot is compared with a Welch's t-test with Bonferroni correction for each fatigue case. The results show a significant difference for some of the fatigue cases, where the controller is either significantly better or there is no significant difference in the overshoot. The fatigue-adaptive game shows consistency across the cases, whereas the baseline does not. Therefore, the fatigue-adaptive game can compete with a person in managing fatigue, while being easier to learn and automatically identifying and removing risky shoulder positions where fatigue changes rapidly. The fatigue-adaptive game can also be played with an industrial robot arm and still demonstrates the capability to manage the fatigue of the two most commonly injured muscles.**

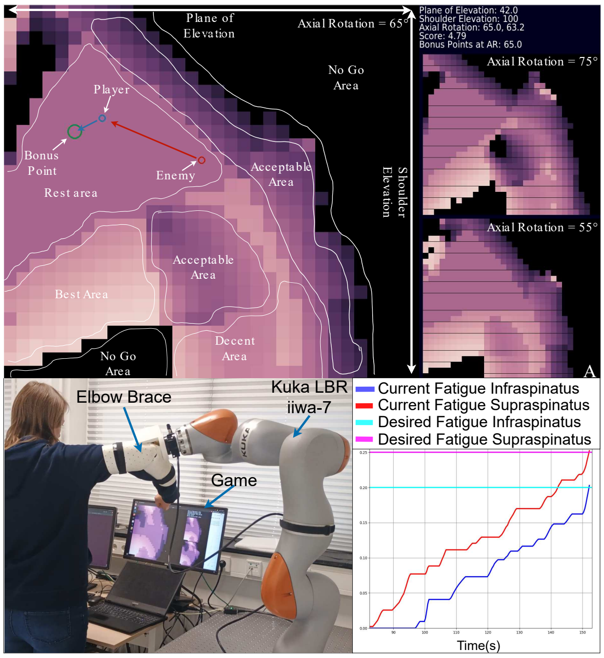

Fig. 1. The top image shows the game. The bottom-left image is the robot setup in the lab, where the patient is wearing a brace connected to the robot arm's endpoint. The bottom-right image illustrates an example of fatigue changing during a game, where the controller is used to manage fatigue. The blue lines correspond to the infraspinatus, and the red lines to the supraspinatus.

I. Introduction

With a growing elderly population, shoulder injuries, especially rotator cuff tears, will become more common. Research has already shown that 22.1% of people have a rotator cuff tear, with the chances of a tear increasing with age [1]. The rotator cuff tendons are more susceptible to tearing than the tendons of the larger shoulder muscles. The supraspinatus tendon is most likely to tear, followed by the infraspinatus, which mostly tears when the supraspinatus is torn. The other two rotator cuff tendons are less likely to tear [2] [3]. Tears in elderly patients can never fully recover, but their impact can be lessened with physiotherapy and exercise to strengthen the muscles and improve the range of motion. A tear can limit a patient's mobility and make some daily activities difficult if they require lifting or an extensive range of motion.

There are two main types of rehabilitation exercises, passive and active. With passive exercises, the physiotherapist will move the limb through an exercise. With active exercises, the patient moves their limb while the physiotherapist corrects to ensure proper execution and prevent muscle overuse. In these exercises, the shoulder muscles should not be overworked because fatigue can worsen the injury [4], as fatigue can cause microstructural damage in the tendon [5]. Guiding the patient can put physical strain on the physiotherapist and is time-consuming; additionally, the physiotherapist speaks with patients to keep them motivated and entertained. To alleviate the physical therapist's workload, robotic physiotherapy could take over some of the demanding tasks. This will require numerous safety features to prevent re-injury, as the robot lacks awareness of the patient's state. Therefore, controlling muscle fatigue could be an interesting and potentially beneficial strategy for preventing patients from reinjuring their muscles during robotic rehabilitation [6].

The use of robots in physiotherapy also lacks social interaction, which can make sessions less engaging and motivating. A patient's motivation can impact the outcome of the rehabilitation. If a patient is unmotivated, they may stop exercising, which can be detrimental to their recovery from a shoulder injury [7]. Incorporating a game can help keep patients motivated and entertained [7] [8]. Therefore, we would like to use a game to encourage patients to engage in and enjoy their exercises.

Most robotic physiotherapy research is done with an exoskeleton. The exoskeletons can mimic the shoulder's movement, allowing for the articulation of each degree of freedom individually. However, properly aligning the joints for different patients can be a challenge [9]. This is an issue if multiple patients are to be helped. The benefit of an industrial collaborative robot arm is that it is only connected to the patient at the endpoint, making it simple to connect to the patient. Collaborative robot arms are also already designed for safe human-robot interactions. They are also more common and less expensive.

For the patient's safety, the robot arm utilizes a controller, such as an impedance or admittance controller, that guides the patient. All the while, the patient is capable of opposing the robot without too much effort in case the robot goes over the patient's limits [10]. This is the primary safety feature for injury prevention. However, the patient's state is barely taken into account during robotic shoulder rehabilitation. In [11], the authors propose a method to optimize muscle strain, enabling a collaborative robot to follow the optimized path during passive exercises. In [12], the researchers mapped a patient's discomfort area via a handheld device. In [13], the researchers created a multisensor approach. They used Electrooculography, Electromyography (EMG), and eye-tracking to determine the patient's intention to move in a virtual reality game. Then, based on the fused EMG signals with position and force measurements, the level of assistance for an exercise is determined.

In a recent study [14], researchers used a muscle fatigue estimate to rehabilitate the wrist. Muscle fatigue was used as a safety measure to determine the total torque a patient would need to supply during the session without overusing the wrist muscles. In [15], the authors also measured surface EMG to evaluate fatigue in some of the larger muscles in the arm to adapt the assistance a patient needs to perform the exercise. In another study [16], researchers used muscle fatigue in a feedback loop in a game where participants had to maintain a force to attack an enemy; if the fatigue became too high, the force would be decreased. This was done to protect the muscles from overuse while exercising with more enjoyment.

Most of the papers describe muscle fatigue as the loss of force-generating capacity [17]. In research, where a continuous force is maintained for a duration, researchers analyze the maximum endurance time to give information about fatigue [18]. The unit of fatigue is more ambiguous if the force is not constant. Researchers then described it as the percentage of the maximum force capacity [19].

An important aspect missing in the rehabilitation literature is the integration of non-repetitive movement and changing forces while protecting the most commonly injured muscles from overuse. The research does not yet link the components of gaming, fatigue, and active movement physiotherapy together. Therefore, this research proposes a fatigue-adaptive game to protect the infraspinatus and supraspinatus from overuse. As fatigue can exacerbate the shoulder injury. At the same time in this game, the exerted forces may change, and the patient has the freedom to choose how to move their shoulder. This research enables patients to move their arm through a range of motion encompassing the plane of elevation, shoulder elevation, and axial rotation. Figure 2 displays the angles of the shoulder and an image of the rotator cuff muscles.

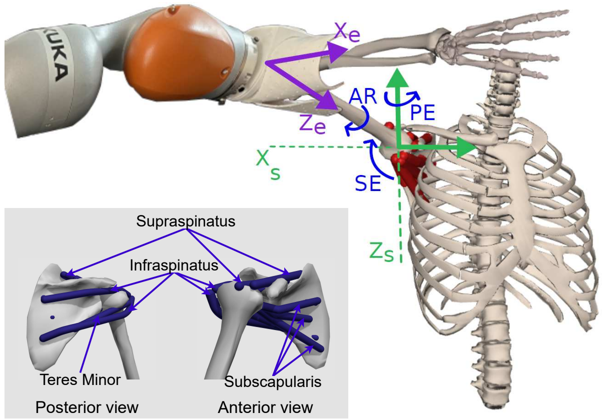

Fig. 2. The three angles of the shoulder considered in this research. The plane of elevation is moving the arm in front of or behind the body. The shoulder elevation determines how high the elbow points. The Axial rotation is rotating the arm. This image is adapted from [20]. The shoulders in the corner display the rotator cuff muscles and their location on the scapula. The supraspinatus is connected to the top of the scapula, and the infraspinatus is connected to the back of the scapula.

While creating an engaging game or testing the fatigue model's applicability and adaptability to various individuals could both be interesting research topics. The scope of this research focuses on controlling muscle fatigue with a game for the two most commonly injured muscles. Thus, the research question this paper addresses is: How can muscle fatigue in the infraspinatus and supraspinatus be controlled during gamified robot physiotherapy to achieve a desired fatigue level while minimizing overshoot of the desired fatigue?

II. Methods

To protect the infraspinatus and supraspinatus muscles from overuse during robotic physiotherapy and make physical therapy engaging, a fatigue-adaptive game is designed that can be played with the robot arm. A cat-and-mouse game limits the shoulder positions to ensure fatigue builds up as needed, while using an enemy and bonus points to encourage the player to move their shoulder. Figure 3 shows an overview of the entire system. The robot monitors the patient's shoulder angles and elbow forces (II-D). These are used in the rapid muscle redundancy solver to determine the forces exerted by the muscle, which the fatigue model uses to estimate fatigue (II-A). Then the balancer (II-B) limits the positions of the shoulder based on the current fatigue for the game(II-C).

A. RMR-Solver + Fatigue Model

The fatigue is estimated using the rapid muscle redundancy (RMR) solver, which is introduced in [21]. The researchers aimed to create a more computationally efficient model while maintaining the accuracy of another commonly employed model. The RMR-solver optimizes the forces for all the

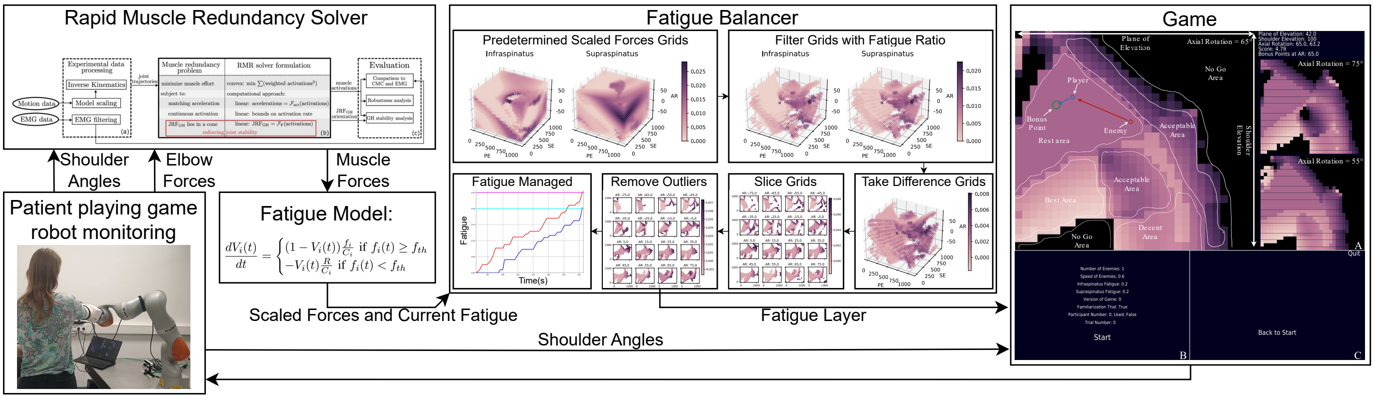

Fig. 3. This diagram shows the steps of the fatigue-adaptive game. The patient plays the game while the robot monitors the patient's state. The robot arm position and load cell send their data to the rapid muscle redundancy solver [21], where the individual shoulder muscle force contribution is determined and sent to the fatigue model [22]. The fatigue model updates the current fatigue and sends the scaled forces to the fatigue balancer. The fatigue balancer utilizes these values to update and filter a grid, managing fatigue. The correct slice of the fatigue grid is sent to the game as a background image.

shoulder muscles by minimizing the effort of the muscles. This is done to determine the distribution of the forces exerted by the rotator cuff muscles and the other shoulder muscles.

Then, the human muscle fatigue model from [22] is used to estimate the fatigue of the rotator cuff muscles based on the exerted force by these muscles. A drawback of this model is the use of the same parameters, like the capacity, recovery rate, or force threshold, for each patient. In future research, the model can be adapted to each patient; currently, the parameters are set to general values for all patients. Equation (1) shows the fatigue model.

$$\frac{dV_i(t)}{dt} = \begin{cases} (1 - V_i(t))\frac{f_i}{C_i} \text{ if } f_i(t) \geq f_{th} \\ -V_i(t)\frac{R}{C_i} \text{ if } f_i(t) < f_{th} \end{cases} \quad (1)$$

In this model, the difference in fatigue (V_i) for each muscle (i) is calculated. The fatigue increases if the force (f_i) determined by the RMR-solver is larger than the force recovery threshold (f_{th}). The change in fatigue is dependent on the current fatigue level and the force divided by the muscle's capacity (C_i) to exert forces. The fatigue decreases if the force is lower than the threshold and is dependent on the current fatigue and recovery rate (R) divided by the capacity.

During the research, various tests were conducted to determine the effect of different fatigue model settings. These tests were used to select the setting for the human factors experiment. The results are presented in the appendices A to E, and the values used in this research are listed in Table II. The tests employ a fatigue grid unscaled by the current fatigue and independent of time. So, for each position in the range of motion, the exerted force of the shoulder muscle is determined and only scaled by the capacity, which is referred to as the scaled forces.

B. Fatigue Balancer

This research focuses on controlling fatigue and minimizing the overuse of the most commonly injured shoulder muscles, the supraspinatus and infraspinatus. To manage fatigue, muscles need to respond differently in a particular position or under a force, so the fatigue changes uniquely for each muscle. This enables the selection of positions or forces to control the muscle fatigue. To accomplish this, we considered two control strategies: changing the forces needed to be applied by the shoulder or limiting the range of motion of the shoulder. Limiting the range of motion was implemented due to the uncertainties with changing the forces. The implementation is described in more detail in section II-B3.

1) Forces: To manage fatigue by adjusting the forces exerted by the patient, we considered three possibilities. Option one: the forces could be changed for a specific motion, for example, drawing a circle or waving your elbow. Option two: forces could be changed in some areas, for instance, in front of your body, but not behind. Option three: The forces would vary for some directions. However, during some simulated tests results in E, the impact of forces on the fatigue of the rotator cuff was small unless the exerted forces were high, which is not recommended for an injured arm. The direction of the forces also appears to have little impact, as the areas affected by each direction were similar in size and location.

For the first option, the fatigue would need to differ for each movement, and the effect of the force would also need to be mapped. This option requires a dataset beforehand, some assurance that the motion is executed correctly, and control over how often a movement is executed. The second option can be challenging because increasing the force in some areas has no effect, especially when a small force is applied. While in other regions, both muscle might increase their fatigue with a similar value. The third option is likely not effective because the simulated test showed that the directions of force have a similar impact on fatigue.

2) Range of Motion: The fatigue can be controlled by limiting the positions in which the game is played. From some simulated tests, it appears that there are different areas where one of the muscles fatigues more than the other, as shown in Figure 9. Therefore, if the supraspinatus muscle needs to fatigue twice as much as the infraspinatus, the player could be forced to stay in the positions where the supraspinatus roughly has a value twice as large as the infraspinatus. Then the fatigue will reach the desired level, especially if this area is updated with the latest fatigue estimates.

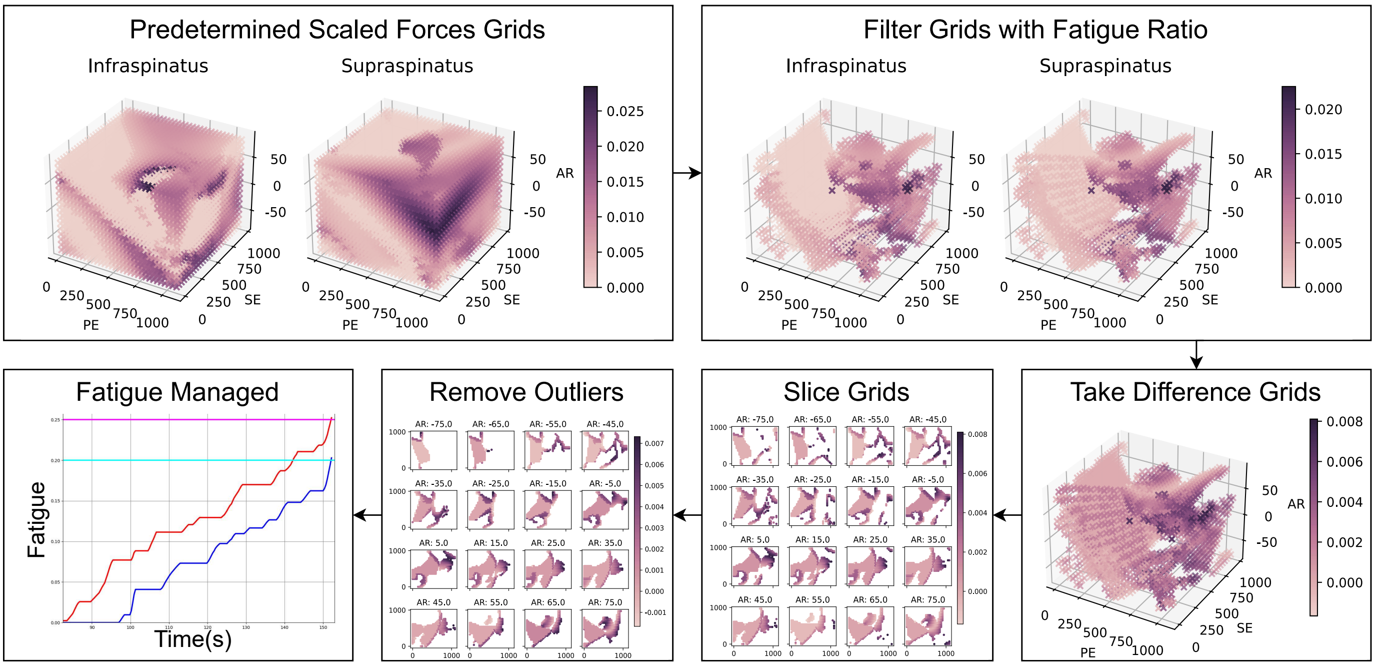

Fig. 4. The steps of the fatigue balancer. The balancer begins with a predetermined scaled force grid where positions are maintained that match the ratio of the needed fatigue for each muscle. Then the difference between the grids is taken, where the lighter areas fatigue the muscle that needs to fatigue the most. Then the grid is sliced into different axial rotation layers, and the outliers are removed. The result is the fatigue layer, which serves as the game's background.

3) Fatigue Balancer Implementation: Controlling fatigue by changing the area was chosen because there are many uncertainties with the force control. The area controller was implemented by starting with pre-calculating a fatigue grid, which is not scaled by the current fatigue. The grid points are the plane of elevation, shoulder elevation, and axial rotation, divided into several positions. For each of these points, the fatigue of the rotator cuff muscles is estimated. During the game, this grid is updated to get a more accurate estimate of the fatigue.

Then, based on the ratio between the needed fatigue of both muscles, the grids are filtered to determine acceptable areas where the game can be played. The acceptable areas are where the fatigue of one muscle is roughly the fatigue value of the other muscles multiplied by the ratio.

$$\begin{bmatrix} z_i \\ z_s \end{bmatrix} = \begin{bmatrix} x_i - y_i \\ x_s - y_s \end{bmatrix} \tag{2}$$

In (2), the variable z represents the needed fatigue (the increase in fatigue to reach the desired fatigue), x represents the desired fatigue (the maximum value the fatigue can reach), and y represents the current fatigue. Index i belongs to the infraspinatus, and index s represents the supraspinatus.

$$\begin{gathered} r = z_n/z_m \\ r \cdot G_m - thr \leq G_n \leq r \cdot G_m + thr \\ diff = G_n[mask] - G_m[mask] \end{gathered}$$

$$\begin{cases} m = i, n = s \text{ if } z_s > z_i \\ m = s, n = i \text{ otherwise} \end{cases} \tag{3}$$

In (3), the needed fatigue calculates the ratio (r). With this, grid points (G) are filtered to be near the needed fatigue ratio enclosed by the threshold (thr).

To illustrate what (3) entails, the following example is given. Suppose the infraspinatus fatigue is currently $y_i = 0.1$ and needs to go to $x_i = 0.2$. The needed fatigue would be $z_i = 0.1$. And if the needed fatigue of the supraspinatus is $z_s = 0.15$. Then $z_s > z_i$ and the ratio would be $r = 0.15/0.1 = 1.5$. So the grid points where the game can be played are where the supraspinatus fatigue values are approximately 1.5 times larger than the infraspinatus fatigue values.

The areas where the muscles tire as needed are sliced in several axial rotation layers to make the fatigue grid easier to display in the game. Then the points not attached to the largest area in each layer are removed. This ensures that the player mostly travels in the acceptable areas. The complete fatigue balancer steps are shown in Image 4

These steps from Figure 4 are executed three times a second to ensure the desired fatigue is reached. However, this means that the areas can change every time step, and the game should be able to accommodate this. This makes playing a game with an unchangeable field, such as a word search, impossible. Furthermore, the game should encourage a patient to keep moving their shoulder, because a few positions are enough to reach their desired fatigue levels. Lastly, it only takes two or three minutes to reach most fatigue levels when moving the shoulder; the game will have to be quick, otherwise the patient will be interrupted mid-game.

C. Game Design

To design an appropriate game for the method, several requirements must be met. The game must be a 3D game, as the shoulder has three different angles of movement and can use a grid that adapts to the fatigue. To visualize the 3D grid, the game must be able to switch between slices of the grid,

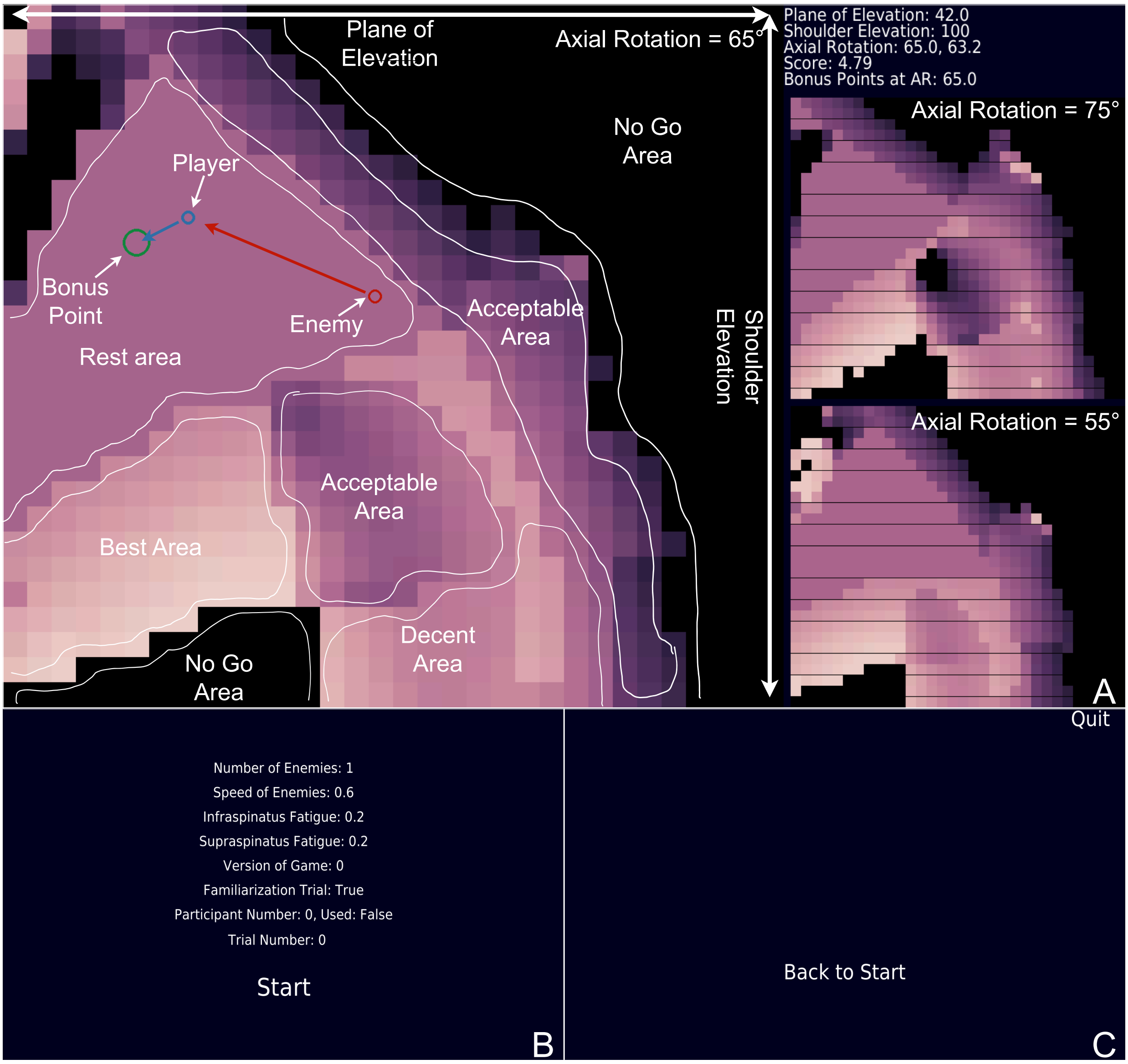

Fig. 5. The start, end, and main game screens. The main game screen (A) shows a fatigue map for the axial rotation of 65 degrees. The plane of elevation is linked to the horizontal axis, and the vertical axis is linked to the shoulder elevation. The blue dot is the player, the green dot is the bonus point, and the red circle is the enemy. In the top right corner, the current angle position is visible above the score and the location of the bonus point. The two maps below the game information display the fatigue maps of the closest axial rotation values. The start screen (B) contains the game and the experiment settings. The stop screen (C) could display a scoreboard, but currently, it only has a button to return to the start screen and stop the game.

so the slice of the current axial rotation layer can be shown. Furthermore, a game only takes a few minutes, so most games, for instance, a puzzle, would take too long.

Therefore, the game is designed as a cat-and-mouse game where the player must dodge the enemy and collect bonus points. Figure 5 displays the different screens of the game. The player moves the blue dot, and its location in the game is dependent on the shoulder angles. The red enemy encourages the player to move their arm, and the green bonus points promote moving into different axial rotation slices. The game background is composed of acceptable shoulder angles points, where the fatigue of the supraspinatus and infraspinatus increases appropriately, which are displayed in purple. The areas where the fatigue grows unbalanced are shown in black. The background is one layer of the grid, showing the plane of elevation and the shoulder elevation at a specified axial rotation value, allowing players to navigate through other values.

The player's score, shown in the top right corner, increases when they stay in the purple areas. In the black area, the score decreases to discourage moving into the unwanted shoulder positions. Hitting the enemy has the same effect on the score and discourages staying in the same shoulder position. A player will receive bonus points by moving to a point shown in green, which could be in a different axial rotation layer. This encourages the player to rotate their upper arm. The bonus points disappear if the area underneath is black, ensuring that fatigue is being managed correctly. The start screen displays the settings for the enemies and the desired fatigue level.

D. Robot Controller

When using the robot with the fatigue controller, the robot is supposed to be as unobstructive as possible, so it doesn't impede shoulder motion. The KuKa robot arm itself has a built-in gravity compensation, so it does not collapse under its own weight. However, with the force sensor, arm brace, and the patient's arm itself, gravity compensation is not perfect, and the shoulder has to exert an extra force to keep the Kuka arm in position. Therefore, an impedance controller helps maintain a position unless the position differs sufficiently or the exerted torque aligned with the axial rotation is sufficient. Thus, when the patient moves their arm, which is connected at the elbow with a brace, it feels as if the robot moves easily along. Then, the robot publishes its endpoint position and forces, which are transformed into the required reference frames and used in the RMR-solver, fatigue model, and game.

III. Experiment

To validate the fatigue-adaptive game, a human factors experiment was conducted with twenty participants on a laptop with a mouse. The experiment was approved by the Human Research Ethics Committee (HREC) of TU Delft. The experiment will test the fatigue-adaptive game, henceforth also referred to as the controller, against a baseline where participants will control the fatigue for the infraspinatus and supraspinatus muscles themselves. The robot arm will only demonstrate the fatigue-adaptive game capabilities to determine if future research into the game is viable and identify potential issues.

A. Fatigue-Adaptive Game Experiment Task

To test the fatigue-adaptive controller, it will be compared to a baseline. The controller and baseline will both be played on a laptop with a mouse. The primary hypothesis for this human factor experiment is that there is a difference in overshoot between the controller and the baseline. In the baseline, the participant has a complete overview of all the necessary information to control fatigue. The background changes only in increments of axial rotation, and the background displays the difference between the fatigue of the infraspinatus and supraspinatus. Therefore, the supraspinatus fatigues more in the brighter areas and the infraspinatus in the darker areas. With this and the plot, the fatigue can be managed. A figure of the baseline game and plot is shown in Figure 6. The only difference between the baseline and the controller is the game's background and the use of the fatigue plot in the baseline.

The most important part is to prevent overexertion of the shoulder muscles, so the fatigue should not overshoot the desired fatigue level set at the beginning of the game. The desired fatigue level can differ for both muscles, and they will not always reach their respective desired fatigue levels simultaneously. The game will end when both muscles have crossed their desired fatigue level.

B. Data Collection

The twenty participants began the experiment by becoming acquainted with the game, and then played the six games where data were collected. They played three cases of desired fatigue levels. First, they played with the fatigue-adaptive controller. Second, with the baseline, it is possible to use the controller's information to know which areas are better than others in the baseline. For the experiment, the participant needed to know which version and, for the baseline, which case was being played. Therefore, before the start of a game, the experimenter provided a reminder of the rules and the version. For calculating the overshoot, fatigue is recorded. At the same time, the position and background colors are recorded. The protocol of the experiment is placed in Appendix G.

C. Data Analysis

From the data gathered, the overshoot was calculated by taking the maximum fatigue value reached during or at the end of the game. The absolute difference was considered instead of the percentage, because it is essential to prevent fatigue from building up to more than desired. If the infraspinatus overshoots, then the overshoot is positive; otherwise, it is negative. In Appendix H, two examples of the overshoot are shown in Figure 22.

Between the controller and the baseline version of the game, we wanted to investigate whether there was a significant difference in the means of the overshoot. The overshoot data is checked for normality and homogeneity of variance to pick a suitable statistical test. The expectation is that practice beforehand gives a person the time to get experienced with the game and both versions. For the controller, there is no difference between the fatigue cases in how the fatigue is controlled or the game is played, and thus, the value of the overshoot should be similar. From my baseline tests in I, the same strategy could be used for each case, and as long as you paid attention to the current fatigue plots, the overshoot was minimized. With practice, a participant can become familiar enough with the fatigue map to determine the risky areas where one muscle fatigues rapidly. Therefore, the order of the cases seemed trivial, and we preset the order of the cases to have one less factor impacting the human factor experiment. In the experiment, the primary hypothesis is that there is a difference in overshoot between the fatigue controller and when a participant controls fatigue. The null hypothesis would then be that there is no difference between the baseline and the controller.

Considering the points described above, the statistical test suitable for this experiment would be an independent t-test comparing the mean overshoots between the two versions and placing the overshoots from the separate cases in the same group for each version. A power analysis, shown in I, with ten test runs, indicated that 43 participants are required before any significant difference becomes noticeable.

D. Pilot Study

Before the HREC approved this experiment, a two-person pilot study was conducted to test the experimental setup and whether the experiment was clear. The pilot study encountered some issues with understanding the baseline and confusion about the version being played. Therefore, the version and case

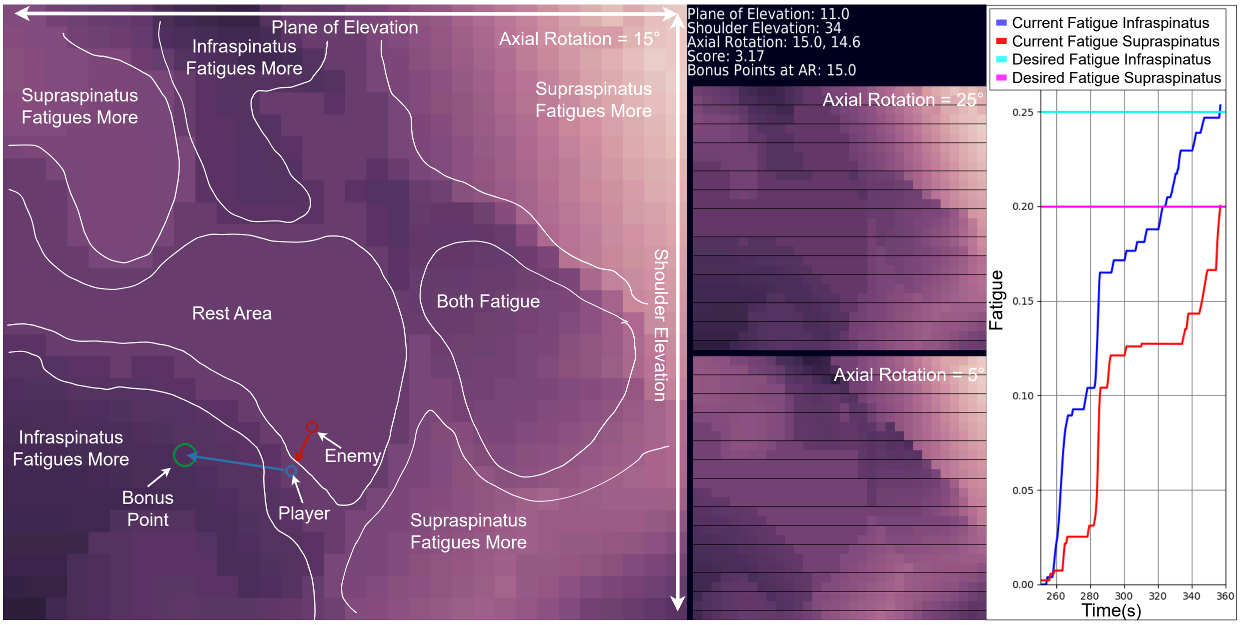

Fig. 6. The Baseline background shows the difference between the infraspinatus and supraspinatus. In the lighter areas, the supraspinatus fatigue increases more, and in the darker areas, the infraspinatus fatigue increases more. However, some areas with the same color could mean that the muscles stay fatigued, while other areas, both muscles could increase at the same rate. The plots visualize the fatigue for the infraspinatus during the game. The desired end fatigue is also shown, where blue and light blue correspond to the infraspinatus and the red and pink lines to the supraspinatus.

are also shown in the game explanation document to clarify the order. We reminded the participants of the game's aim and rules at the start of each of the six tests, and they could only start if they understood both versions of the game.

E. Robot Demonstration

To showcase the potential of the fatigue-adaptive game, a demonstration was performed with the robot arm. The robot arm is set up in the lab on a table with the game on the screen in front of the player, as shown in Figure 1. When playing the game with the robot, there are some differences. The forces exerted by the patient are taken into account, the axial rotation changes quickly, and some positions at the edge of the range of motion are difficult to reach. Two of my colleagues and I conducted tests to examine the overshoot in various cases. This is done to determine if there is any value in the game when it is used with the robot and to identify any issues that should be addressed if this research is continued.

IV. Results

A. Fatigue-Adaptive Game Experiment

The results displayed here come from the fatigue-adaptive game experiment, where the fatigue-adaptive game described in II is compared to a baseline in which participants control fatigue by monitoring a plot on the laptop. The raw data of the fatigue growing throughout the game for each participant is shown in the Appendix J in the Figures 28 to 30. The data from the overshoot of both versions is normally distributed, as all the overshoot points lie between the 95% boundaries, as can be seen in the Quantile-Quantile plots of Figure 31.

The assumption of independence between the versions or cases is not entirely correct for this experiment, as participants

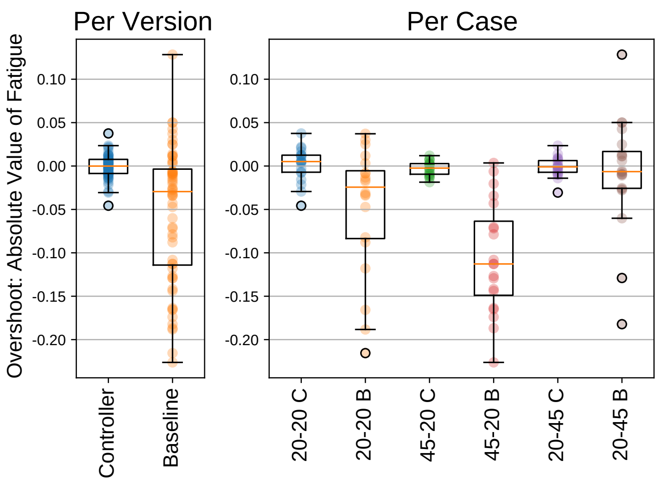

Fig. 7. On the left are the box plots for the combined cases of the controller and baseline. The overshoot mean of the controller is around zero, and the variance is ten times smaller than the baseline. The baseline overshoot mean is shifted; the supraspinatus overshoots more than the infraspinatus. On the right are the Box plots for each case, showing the results for each version. The C stands for the controller, and the B for the baseline. The numbers indicate the desired fatigue percentage for each case, where the first value represents the infraspinatus and the second supraspinatus. The controller variances and means are consistent for each case. The baseline means are all different, and only one overshoot is close to zero. The baseline variances are larger than their controller counterpart.

may have improved during the experiment. However, we believe these improvements will be minimal as the participants could practice beforehand and had to understand the entire game before starting the experiment.

Figure 7 displays the results of the controller and the baseline in box plots. The box plots should be centered around

TABLE I
RESULTS OF THE WELCH'S T-TEST EXPERIMENT CALCULATED FOR EACH CASE.

	SDR	Effect size	P-value
Case 1: 0.20-0.20	3.80	-0.935	0.00737
Case 2: 0.45-0.20	7.58	-2.254	$7.29e-07$
Case 3: 0.20-0.45	5.66	-0.145	0.651

zero, as the goal is to minimize the overshoot. In the box plots per version, a clear difference between the two versions of the game is visible. The overshoot of the controller is centered around zero and has a variance of approximately 0.0002. For the baseline version, the mean is approximately -0.05, and the variance is approximately 0.0059.

However, the box plots per case in Figure 7 tell a different story. Here, the controller (labels containing a C) has a similar mean and box per case. Thus, being consistent for each case. The box plots for the baseline (labels containing a B) do show dissimilarities between the cases. Case three: infraspinatus 20% and supraspinatus 45% fatigue (20-45 B), the box is quite a bit smaller, and the median is near zero. The other two cases have a larger box, and the median is shifted away from zero. Showing that the case affects the baseline overshoot. Then, the variance between the groups is not sufficiently similar to use the independent t-test. This is because the standard deviation ratio(SDR) is not equal to one [23]. Therefore, the Welch's t-test is used, which does not assume homogeneity of variance.

The differences between the cases are also clearly visible in the Welch's t-test results in Table I. The Welch's t-test is performed for each case between the versions, indicating the differences in overshoot of the baseline compared to the consistent overshoot of the controller.

B. Robot Demonstration

The robot demonstration showed that the fatigue-adaptive game can be played with the robot and performs similarly to playing the fatigue-adaptive game on a laptop. The plots in Appendix K demonstrate several trials of the fatigue changing in a game while playing with the robot. There are some noticeable differences between playing the game on a laptop and with the robot arm. The most noticeable difference is the limited range of motion of the robot arm, and the joints must be aligned correctly to reach several shoulder positions. This issue would need to be resolved for future research. My colleagues and I required several trials to get familiar with how arm movement is related to movement in the game and the limits of the robot arm. It is easier to understand the game if there is an understanding of the three shoulder angles beforehand.

V. DISCUSSION

The question this research considered was: How can muscle fatigue in the infraspinatus and supraspinatus be controlled during gamified robot physiotherapy to achieve a desired fatigue level while minimizing overshoot of the desired fatigue? For this, a fatigue-adaptive game, as explained in II, was created, and to validate it, a human factors experiment was conducted with the controller against a baseline where the participant controlled the fatigue of the two muscles themselves. Lastly, a demonstration with the robot showcases the possibilities of a fatigue-adaptive game for robotic shoulder rehabilitation.

A. Fatigue-Adaptive Game Experiment

The Fatigue-Adaptive Game Experiment tested the controller described in II against a baseline where participants controlled fatigue by monitoring a current fatigue plot. The data from the experiment meet the condition of normality. However, the baseline cases were more distinctive than expected, meaning that these three cases cannot be combined to compare only the versions. Therefore, a Welch's t-test is necessary for each case. The primary hypotheses for each of the three cases would be that there is a difference in overshoot between the fatigue controller and the baseline. The null hypotheses for each case would be that there is no difference in the overshoot between the fatigue controller and the baseline.

With more tests on the same dataset and a possible dependence between the cases, the t-test needs a Bonferroni correction to minimize the experiment-wise error rate. Thus, the p-value acceptance boundary is set to $p = 0.05/3 = 0.0167$. From the box plots in 7, the overshoots of the first two cases of the baseline are notably different, while the third case looks quite similar to the controller. This is reflected in the p-values from Table I. Therefore, only two of the individual null hypotheses can be rejected, while the universal null hypothesis, as stated in III-A, cannot be rejected.

The differences between the baseline cases could stem from several factors. For example, learning the fatigue map during the experiment or gaining more experience in dividing attention between the plot and the game. Another cause could be that the third case is the most forgiving, as the supraspinatus overloads more rapidly than the infraspinatus, causing the infraspinatus to overshoot less often. Occasionally, a bonus point is spawned in a risky area, and some participants wanted to get the bonus point rather than minimize the overshoot. Most of the points mentioned above relate to experience in the game and knowing where the better areas are for controlling fatigue. Ultimately, if the participants practiced more with the baseline version, the overshoot would have been closer to zero.

To conclude, there are some noticeable differences between the versions of the games. There is no significant difference between the versions, and the null hypothesis cannot be rejected. Nevertheless, the controller minimizes the overshoot of fatigue at least as well as a person does while showing consistency over the three cases. Furthermore, the controller requires less practice because attention is not split between two screens, and the risky areas are automatically removed, so fatigue does not overshoot as quickly.

B. Robot Demonstration

The fatigue-adaptive game can be played with the KuKa robot arm. The results of the few demonstrations show that the fatigue overshoot is still close to zero and small, as shown in Appendix K. Therefore, the controller displays the capability to manage fatigue as the forces and movements with the robot arm are incorporated.

The demonstration with the robot arm revealed that the primary issues with the robot arm are the limits of its workspace and joints. Joints five and seven need to rotate to the other end of their limit whenever the arm is moved from in front to behind the patient or back. The patient needs to exert extra effort to move around these limits, which can worsen an injury. It would be beneficial if these joints were continuous, or potentially, by improving the nullspace and stiffness settings, without making it more difficult for the patient to overpower the robot. Furthermore, some of the edge positions that you might need to reach for a bonus point in the game are unreachable with the robot arm. This could be solved by a robot with a bigger workspace or by limiting the range of motion in the game.

Another factor to consider is that it takes a couple of trials to understand how the shoulder positions relate to their corresponding positions in the game. This understanding is essential when moving to bonus points, as it is not a straightforward path to follow. The three shoulder angles are closely connected, and changing the plane of elevation and shoulder elevation also leads to a change in axial rotation, mainly because the angle increments are set small, and the robot could block some positions.

The fatigue-adaptive game, as explained in II-B3, with the robot arm, seems capable of managing fatigue to prevent muscle exhaustion when a patient moves their arm within its range of motion, while also considering the forces exerted by the shoulder. This takes a step towards filling a gap in the research while adding a safety feature to robotic physiotherapy.

C. Limitations

In hindsight, a mixed model or ANOVA with a randomized order should have been applied. The cases would have been less dependent on each other, and a mixed model was developed for dealing with an experiment where all participants played all conditions. The data from this experiment are not independent, and the mixed model can generalize the results for both participants and conditions (cases in this research). An ANOVA does not generalize for the conditions [24].

Furthermore, the participants could have benefited from more practice with the baseline to get a better understanding of the risky areas, as they were still learning during the experiment. To correct for the learning effect and test the universal null hypothesis, a correction is needed. Using the Bonferroni correction is controversial because it can produce a very strict p-value and consequently raise the likelihood of a Type II error. However, with only three tests, this value is not very dissimilar from the standard p-value. The Bonferroni correction should be applied in this research to test the universal hypothesis stated in III-A, especially since the hypothesis was altered after the experiment [25].

The experiment only tested three cases of desired fatigue levels. During the testing of the game, other cases were also tried, and most seemed to work, even cases where one was set to 80% and the other to 15%, because there are some areas where one muscle fatigues while the other rests. However, these cases were not tested in the experiment because they are less realistic in physiotherapy, where fatigue should not reach extreme values to prevent re-injury. These extreme cases could showcase the limits of the controller. Therefore, it would be interesting if the controller could manage fatigue that begins with such a gap.

The fatigue model used in the robot demonstration uses the values from Table II, where the model is slowed down by a factor of ten. This means that a game often takes less than three minutes to achieve the desired level of fatigue. Holding your arm up while exerting the forces needed to move the robot arm can be exhausting, but there are rest areas, and it is possible to play several games consecutively. Therefore, the fatigue model seems to overestimate fatigue, especially when no slowdown factor is applied. The controller will also perform better if the games take longer because there will be more time to correct the fatigue.

D. Future research

In future research, it could be interesting to investigate the fatigue model itself. The chosen fatigue model appears to overestimate shoulder fatigue, and some variables in the model are set without a basis in the literature. The model should also be adaptable to different patients to get a more accurate estimate of fatigue, especially for various levels of partial tears in the rotator cuff tendons. Furthermore, it is unclear what the maximum allowable fatigue level is before you injure or re-injure the shoulder. Another interesting aspect could be researching how the forces applied at the elbow impact fatigue. The small tests in Appendix E implied that the impact of the force exerted by the rotor cuff muscles is more dependent on the shoulder position than on the magnitude or direction of the force.

Next, the controller could be extended to four muscles by taking the combined area of the points where the fatigue ratios are calculated between a muscle and the muscle that still needs to tire the most. As long as there are sufficient differences in the way muscles fatigue in various shoulder positions, the controller could still work due to the update rate, especially if there is more time to play the game. Another potential research topic is combining the controller with methods from [11] and [12] to identify and remove areas that cause patient discomfort or pose a high risk of muscle overstrain.

Lastly, an experiment could be conducted with the robot arm to achieve a more realistic representation of the overshoot. Primarily, because using the robot arm is more complex, you need to understand the robot's limitations. Comparing it against the baseline from this research experiment may not be the most representative, as the baseline is demanding to play with the robot because you have to pay attention to fatigue levels, the game, and the robot arm movement. This means that the focus cannot be on both the plot and the game, and fatigue could shoot up, especially if you accidentally move through the wrong area because you cannot follow a straight line. The experiment from II-B3 could also be repeated with a random order to remove the learning factors of the game and thus get more representative results of the overshoot.

VI. Conclusion

In conclusion, this paper introduced a game to manage the fatigue of the infraspinatus and supraspinatus. The human factors experiment showed that the fatigue-adaptive game was not significantly better compared to the baseline at minimizing overshoot of fatigue in every case. Regardless, the controller showed a consistency that the participants were unable to replicate with the baseline. The controller requires less practice because attention is not split between the game and the plot, and the risky areas, where fatigue increases rapidly, are automatically removed, so fatigue does not overshoot as quickly. The fatigue-adaptive game is demonstrated to work with the robot arm, preventing overfatigue of the muscles when the patient moves their shoulder and exerts force, making the fatigue-adaptive game a potential safety feature for robotic shoulder rehabilitation to avoid reinjury of the shoulder.

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APPENDIX

A. Effect of the Path, Velocity, and Acceleration on Fatigue Grid

The effect of the path in creating a fatigue grid is substantial because the controller already needs a fatigue grid at the beginning. Thus, if the results differed too much between grids, the controller could receive an incorrect input and mismanage the fatigue. To test the effect of the path, 12 paths of positions were generated, for which the scaled force was calculated at each position. The plots of the paths are shown in Image 8. The effect of the path on the estimated fatigue is quite noticeable in the plots of Figure 9 if the velocity and acceleration are calculated. Figure 10 shows the difference between all the grids and grid eleven to showcase the differences. The grids are more similar when the paths are also more similar. On the other hand, if the velocity and acceleration are not calculated as in Figure 11, there is hardly any difference between the paths because the positions are independent.

For my experiment, we chose to generate a grid ahead of time without calculating the velocity and acceleration, since a person would not move in the same way as the grid. Therefore, none of the grids would have the correct estimate, and having the velocity and acceleration set to zero would represent the most general case. The settings for this test case were set to the standard values from Table II for the capacity, force threshold, and sampling time. The slowdown factor was set to one, and no force was applied to the elbow.

During the game creation, the controller could utilize any of the generated paths because it adapts at every time step to the current fatigue level, thus adapting swiftly enough to control the fatigue.

B. Effect of Sample Time on Fatigue Grid

The sample time determines how often the RMR-solver and fatigue model can give a prediction, and the effect on the grid is quite noticeable. This is due to the sample time being taken into account in the fatigue estimation. Figure 12, three different values for sample time are plotted; in these plots, the difference is difficult to notice. However, when the difference for each point is calculated as in Figure 13, the differences are more noticeable. Figure 13 shows the first plot, which displays the difference in points between a sample time of 1/5 and 1/3. In the second plot, the difference between 1/2 and 1/3 is shown. The sample time plays a role in the fatigue estimate as it acts as a scaling factor for the fatigue calculation.

In the end, a sample time of 1/3 s was selected because running the RMR-solver, game, controller, and ROS simultaneously limited the RMR-solver to estimate the forces every 1/4 or 3/10 seconds. The estimates also had to be done as quickly as possible to get an accurate prediction during the arm's movement. Therefore, the sample time was set to 1/3 to ensure that all necessary messages reached the RMR-solver in a synchronized fashion. The other settings of the fatigue model can be seen in Table II

C. Effect of Capacity on Fatigue Grid

Fatigue is dependent on the force you are exerting compared to the maximum capacity for exerting forces [22] [26]. So each muscle will have a limit on the force it can exert.

$$C_i = -\frac{f_i^{ref} \cdot T_{end}}{ln(01 - 0.993)} \tag{4}$$

The capacity, as shown in (4), should be determined for each muscle by measuring the individually exerted force of a muscle for a duration. However, there seems to be no research on how to determine the individual forces exerted by the muscles. Therefore, the shoulder is tested for its capacity, and this is used. However, the muscles used will vary depending on the arm's position. With the possibility that the larger, more superficial muscles are the ones that fatigue before the rotator cuff muscles. Therefore, ten times the maximum isometric force of a muscle was picked [27]. Consider this as ten seconds of holding a static limit. When the forces per grid point were computed, some of the values could be near the maximum isometric force of the muscle, meaning that fatigue would increase rapidly. This is due to the fatigue model from (1), where the capacity is set to ten times the maximum isometric force. This causes the fatigue to increase with the force as a percentage of the capacity value. If the force is high, then the percentage is also higher.

In [26], the capacity was set to five times the maximum activation. Then the fatigue still increases rapidly. Therefore, in future research, it would be interesting to determine a method for estimating the maximum individual muscle force capacity to construct a fatigue model more suitable for specific patients.

D. Effect of Recovery Force Threshold on Fatigue Grid

The force threshold determines when someone recovers. If the force is lower than the threshold, the person will recover. The threshold value has to be determined for each muscle. However, currently, there seems to be no research available on this topic. Therefore, we selected a starting point of 1/10 of the maximum isometric force [27]. From my test, the area where the shoulder muscles recover with this threshold is when the arm is held down and to the side of the body, which seems realistic because it is the resting position of the shoulder. Figure 14 shows the area where both the infraspinatus and the supraspinatus muscles recover for two different thresholds. In the second plot, the area is a lot larger. we ended up choosing the lower threshold because the higher threshold has more awkward positions where the axial rotation is at its extremes,

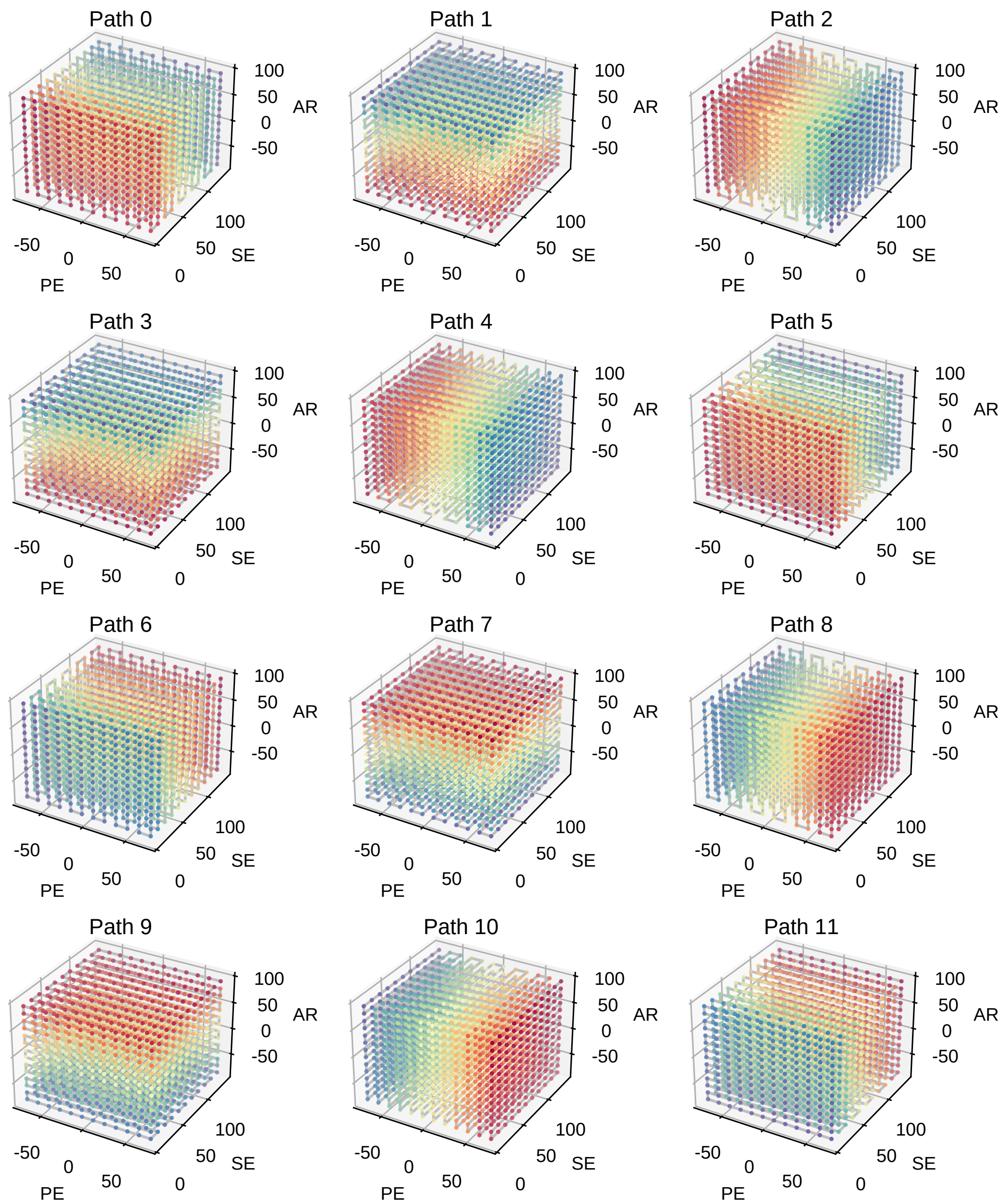

Fig. 8. Grid of angle positions within the limits of the robot and person. The plane of elevation is limited to between $-80°$ and $80°$. The shoulder elevation is between $0°$ and $144°$, and the axial rotation is between $-80°$ and $90°$.

which puts more effort on the shoulder muscles. The other settings of the fatigue model can be seen in Table II

E. Effect of Forces on Fatigue Grid

To examine the effect of forces on the fatigue model, a force is applied in a global direction to the model. The combined force was either 10 Newton or 50 Newton. In the Figures 15 and 16, you can see the effect of the forces on the different points for the Infraspinatus and the Supraspinatus. Most of the plots appear the same from every direction, so in the second set of figures, the difference in fatigue between the force and the control (without a force) is calculated, and only the points that were sufficiently different are retained. As can be seen in Figures 17 and 18, the effect of the forces does not affect all areas equally. However, a similar area appears to be affected for both muscles, regardless of the direction of the force.

The plots with a force of 50 Newton are shown in Figures 19 to 20. The larger force, which should not occur during physiotherapy because it is too high for an injured shoulder, results in a larger area that is different. Nevertheless, there is no evident pattern that the direction of the forces influences one muscle to fatigue more than the other. The settings for these plots are stated in Table II.

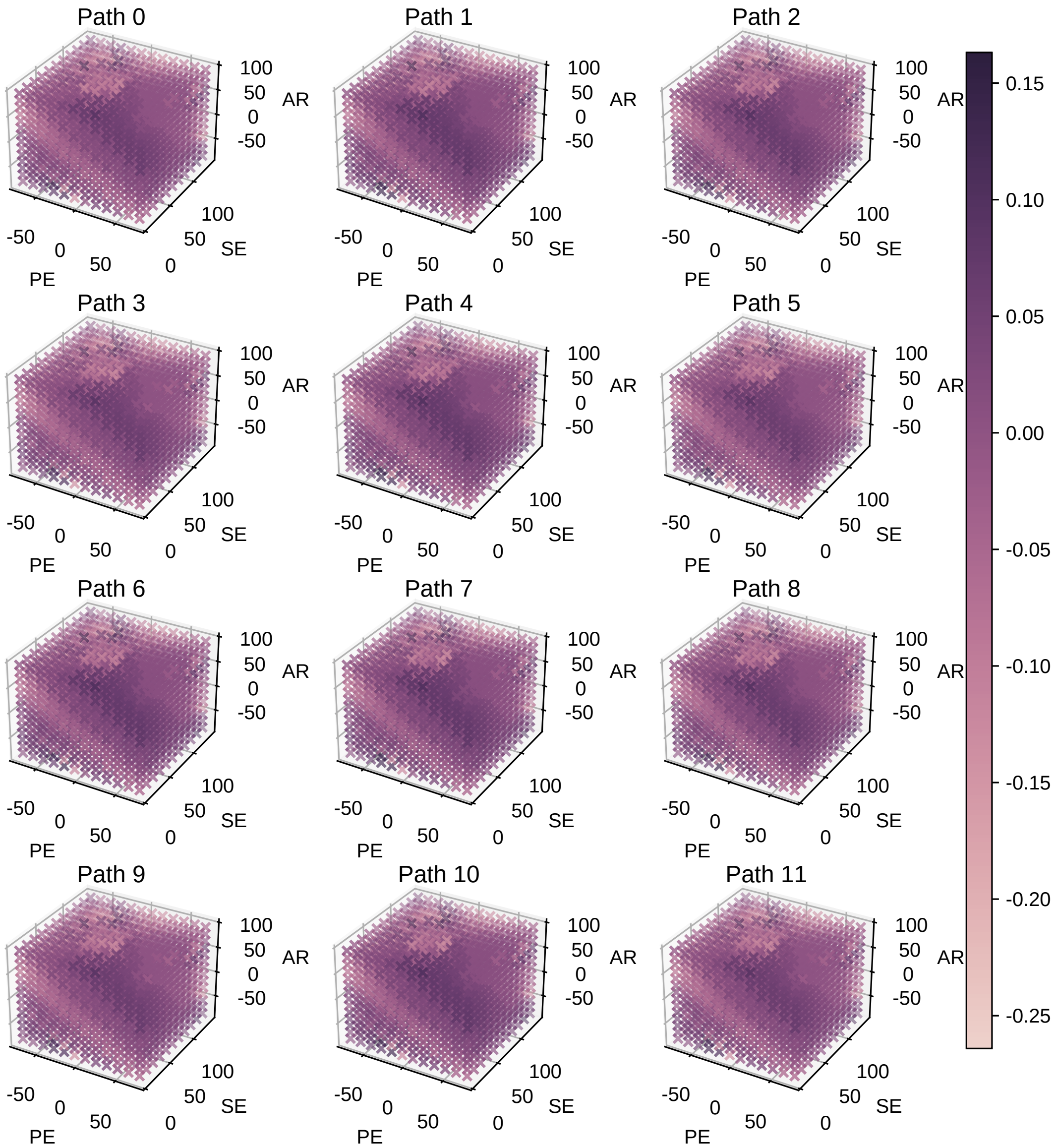

Fig. 9. The difference between the Infraspinatus and Supraspinatus with a Timestep of 1/3 while calculating the velocity and acceleration between the grid points. There is no noticeable difference between the different paths.

F. Important Parameters

The fatigue model settings are defined in the fatigue and RMR-solver scripts. The most important ones are the slow-down factor, capacity, force threshold for when a muscle recovers, sampling time, and endpoint force. The values used in the fatigue model are estimated and are not accurate. The fatigue increases quite quickly. Therefore, the slowdown factor was added. In future research, the fatigue model could be researched further to predict more accurately. None of these parameters influences the fatigue-adaptive game if the similarity threshold in the create grid file is tuned correctly. The slowdown factor and the capacity only impact the duration of the game. The values for the different settings can be seen in Table II

The launch file for the nodes contains all the background, scoreboard, bag, and model paths required in the different nodes. The launch file also defines the number of points by which the shoulder angles are divided.

The create grid file creates the background grid of the game. There are only two important parameters: the threshold for when the fatigue is similar enough, the threshold in (3), and the epsilon value for DBSCAN to remove outliers.

The shoulder publisher file converts the robot's endpoint to shoulder angles and publishes the corresponding shoulder data. All the information used to calculate the angles is defined in the initialization function of the shoulder angle class.

G. Protocol Experiment

The experiment began with welcoming the participant and having them read and sign the informed consent form. Then, the participants were asked to read the game explanation document, or the experimenter read it aloud for them, so that each participant would receive the same information. Figure 21 displays the document with the information. The

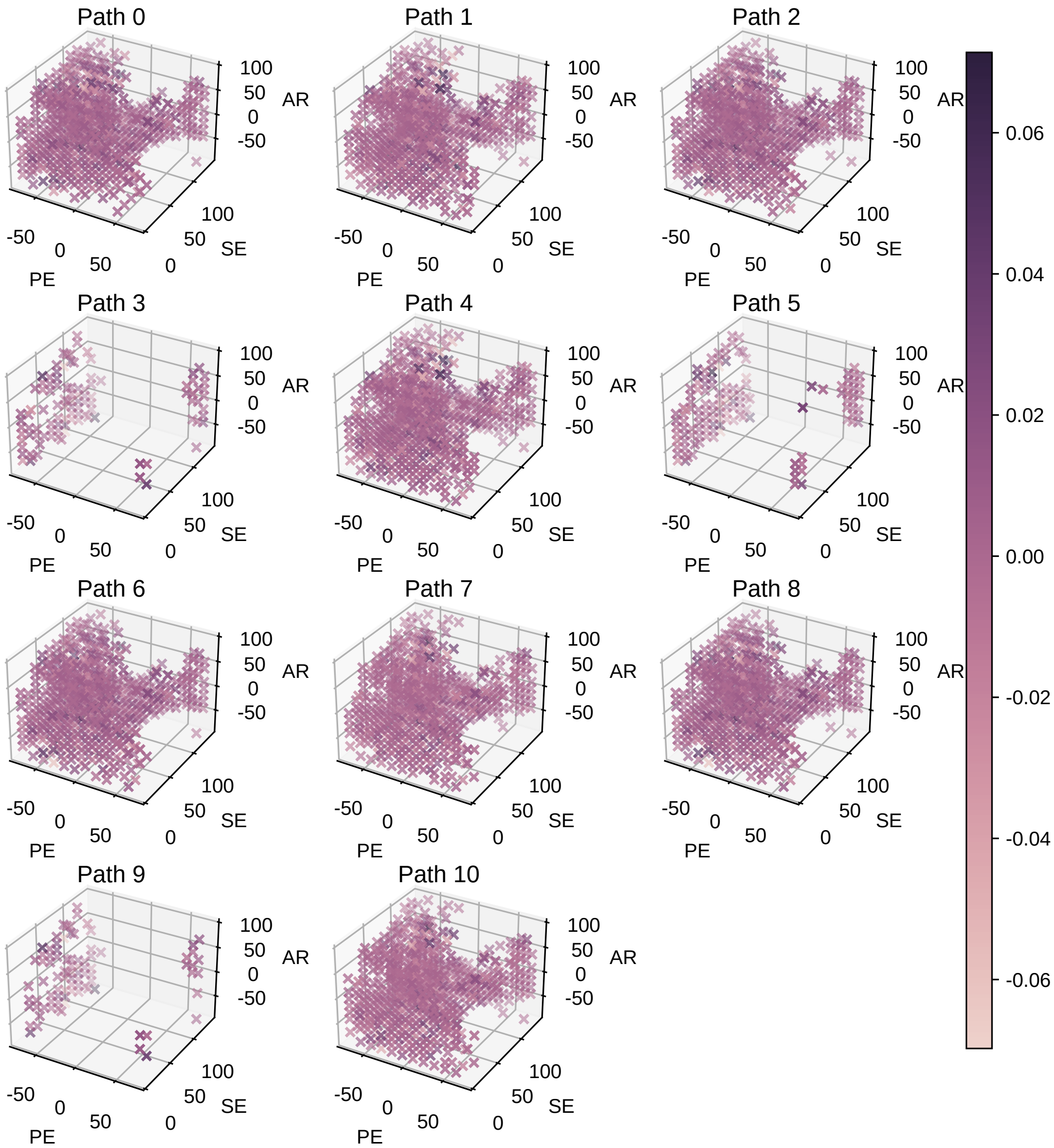

Fig. 10. Highlighting the difference between the paths compared to path eleven. There are some noticeable differences, and they can be quite large. The grids resemble each other closely if the paths are alike.

participants then began practicing the game version zero, while the experimenter explained the controls and game mechanics. The desired fatigue was set to two different values to improve the clarity of the fatigue plot. After the participants understood and could play version zero, the fatigue plot and the colors were explained. Then the participants could practice a couple of times with version one while the experimenter reminded them of the game mechanics and what they should focus on.

Once participants understood both versions, they were asked if they wanted more practice. If this is the case, then they could continue with the practice. Otherwise, the experiment would begin by pressing a button on the start screen to set the cases and automatically record the data. Ahead of each game, the game mechanics were explained, and the fatigue plot was hidden for version zero and shown for version one. The participants played the games in this order:

1) Version zero, Desired Fatigue Infraspinatus 20% and Supraspinatus 20%
2) Version One, Desired Fatigue Infraspinatus 20% and Supraspinatus 20%
3) Version zero, Desired Fatigue Infraspinatus 45% and Supraspinatus 20%
4) Version One, Desired Fatigue Infraspinatus 45% and Supraspinatus 20%
5) Version zero, Desired Fatigue Infraspinatus 20% and Supraspinatus 45%
6) Version One, Desired Fatigue Infraspinatus 20% and Supraspinatus 45%

After all the games were played, the experiment was finished.

H. Data structure

The recorded data is saved in the bag files. For the experiment testing the controllers, the data of fatigue, shoulder

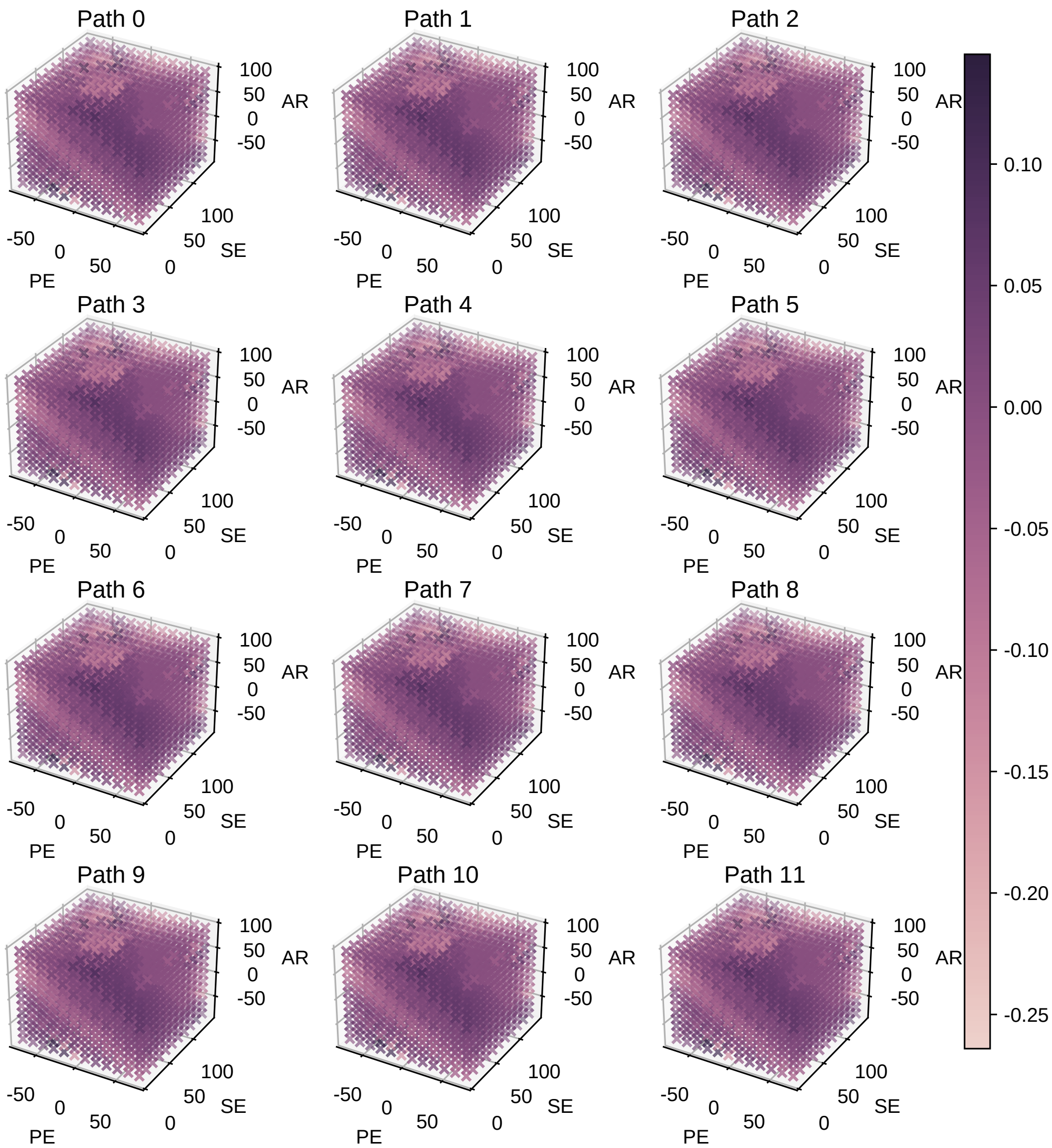

Fig. 11. The difference between the Infraspinatus and Supraspinatus with a Timestep of 1/3 without calculating the velocity and acceleration between the grid points. There is no noticeable difference between the different paths.

angles, and background color are gathered per timestep. For the robot, the fatigue, shoulder angles, and forces are collected. Only the information about fatigue is necessary to determine if the fatigue can be controlled. Nevertheless, the information on the shoulder angles, background, and forces could indicate why the overshoot is higher or if there is a difference in the path between the cases. Two examples of how the overshoot is calculated are shown in Figure 22

I. Power Analysis

A power analysis was used to determine the number of participants necessary for statistical significance in the experiment. Commonly used values for power (0.8) and alpha (0.05) are employed. The effect size was calculated with Cohen's d equation. Then, using these values, the number of needed participants for each version was calculated. The fatigue for each case per version from ten test experiments is shown in Figures 23, 24, and 25. The data was also checked to ensure it followed a normal distribution and had comparable variances. The quantile-quantile plot (Figure 26) indicates that the data mostly follows a normal distribution. However, with real-world data, there is always some noise. we expect the data to follow a normal distribution because the aim is to minimize overshoot, and extreme overshoots are less likely to occur.

There is no clear indication that one muscle is more likely to overshoot than the other. Although at the start, axial rotation angle in the game, the supraspinatus has an area where fatigue builds rapidly, making this a high-risk area. The variances of the overshoot should be similar between the two versions because the same thing is measured in the same game with the same goal. However, the standard deviation ratio disagrees. When I played the game myself for ten tests per case, I found a decent strategy for minimizing overshoot. For case one, where the fatigue needs to reach the same level, this was

TABLE II
THE SETTINGS FOR THE FATIGUE MODEL WITH A SHORT EXPLANATION

Parameter	Value	Explanation and Reasoning
Velocity and Acceleration	True (or False)	The velocity and acceleration have a large impact on the fatigue estimate, so during the experiment, the velocity and acceleration were calculated, but not for the grids in Appendix A.
Sampling time	1/3 s	ROS, robot, game, and RMR solver slowdown the laptop. To synchronize the messages, the sampling time was set as fast as possible without causing issues. The reasoning can be read in Appendix B
Capacity Infraspinatus	$\frac{10*1000}{\ln(1-0.993)}$ N	Set to ten times the maximum exerted isometric force of the infraspinatus superior from [27]. The paper from [26] used five times the maximum activation. The reasoning can be read in Appendix C
Capacity Supraspinatus	$\frac{10*550}{\ln(1-0.993)}$ N	Set to ten times the maximum exerted isometric force of the supraspinatus anterior from [27]. The paper from [26] used five times the maximum activation. The reasoning can be read in Appendix C
Force Threshold Infraspinatus	100 N	Set to one tenth of the maximum exerted isometric force of the infraspinatus superior from [27]. The reasoning can be read in Appendix D
Force Threshold Supraspinatus	55 N	Set to one tenth of the maximum exerted isometric force of the supraspinatus anterior from [27]. The reasoning can be read in Appendix D
Recovery Rate	0.5	Directly taken from this paper [22]. With a recovery rate this slow (also affected by the slowdown factor), it takes minutes for a noticeable decrease to appear. From playing the game, the recovery rate should be around 200 with a slowdown factor of 0.1 to have a clear and usable effect, while still reaching a higher fatigue percentage. However, the recovery then also seems to be impossibly fast. Ultimately, it does not affect the fatigue adaptive controller. It can help to lower the overshoot when the second muscle hits its target, or both muscles could overshoot before the game stops. The value was set to 0.5 because it is in the paper, and more research is needed to determine a realistic value.
Limits Plane of Elevation	-80°, 80°	For the largest workspace for the shoulder, the angles from the opensim model were set at these values, while the robot could still reach these extremes.
Limits Shoulder Elevation	0°,144°	Same reasoning as limits Plane of Elevation
Limits Axial Rotation	-80°,90°	Same reasoning as limits Plane of Elevation
Slowdown Factor	0.1(or 1)	Balanced between not too slow for the game experiment and not too fast for the robot experiment. In this way, all the settings are set to the same values. The slowdown factor was set to 1 for the tests of Appendices A to E. A higher capacity would also slow down the changes in fatigue.

TABLE III
WELCH'S T-TEST CONTROLLER EXPERIMENT

	SDR	Effect size	P-value
Version	3.91	0.352	0.181
Case 0.20-0.20	1.96	0.426	0.357
Case 0.45-0.20	4.15	-0.337	0.231
Case 0.20-0.45	1.24	0.571	0.461

easier because you knew that the lines should stay roughly equal. Otherwise, if one muscle crosses the line, quickly let the other muscle cross the line. The results of the fatigue-adaptive controller and controlling fatigue myself looked similar, with an effect size of approximately 0.352. Therefore, $128/3 \approx 43$ participants are needed in each case to find significance if they played the same way. The box plot of the overshoot per version is viewable in Figure 27 on the left. Here, the overshoot per version is not noticeably different; only the variance is a bit larger. The same is true for the overshoot per case in Figure 27 on the right.

J. Results Experiment

The results of the experiment are shown in the Images 28 to 31. Figure 28 displays the fatigue building up during the game for each participant. Both muscles need to reach a 20% fatigue level. The top two images show the results of the controller for this case, and the bottom two show the baseline. Figures 30 and 29 display the other two cases. Lastly, Figure 31 is the Quantile-Quantile plots, showing that the data for each game is normally distributed.

K. Results Robot Demonstration

Figure 32 shows the raw data of the fatigue for the controller when playing the game with the robot. The first row shows the case $20\% - 20\%$, the second $45\% - 20\%$, and the third $20\% - 45\%$. Figure 33 displays the boxplot of the overshoot for combined cases and each case with dots for every overshoot value. The boxes indicate that the overshoot is close to zero, with similar boxes to the ones from the experiment, suggesting the potential of this method in managing fatigue.

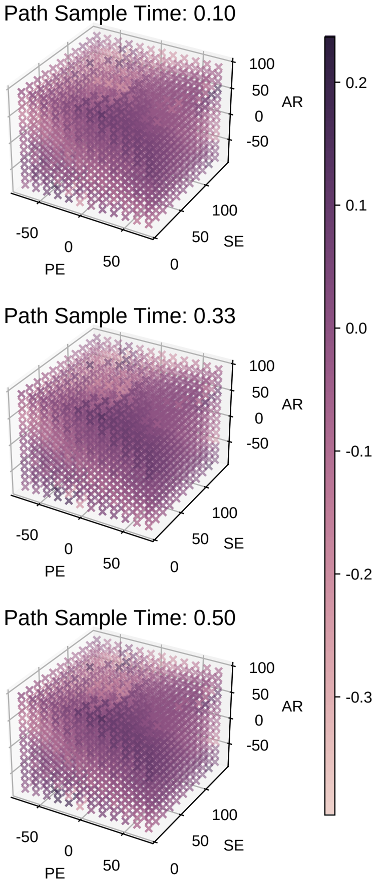

Fig. 12. Grid eleven with three different sampling times. The differences between the values are unnoticeable.

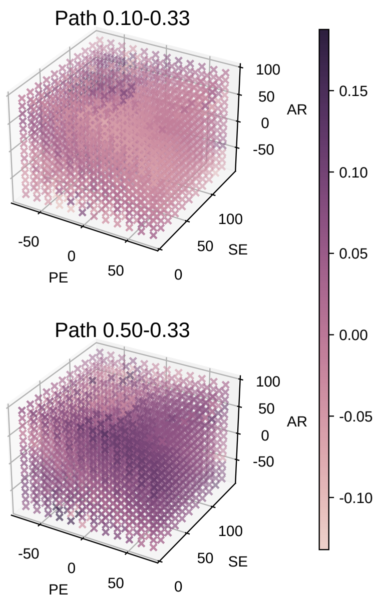

Fig. 13. Difference between sampling time and the standard sampling time of 1/3 in grid eleven. Sampling time is a scaling factor for fatigue. A lower sampling time means that the fatigue values for each point are lower. A higher sampling time means a higher fatigue value.

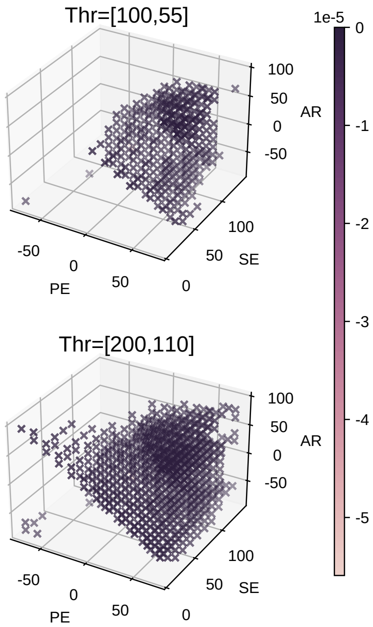

Fig. 14. The resting area with two different thresholds. A lower recovery threshold has a smaller area of rest. The recovery area is to the side or in front of the body while the arm is not lifted too far, and the axial rotation is not twisting the forearm away from the body.

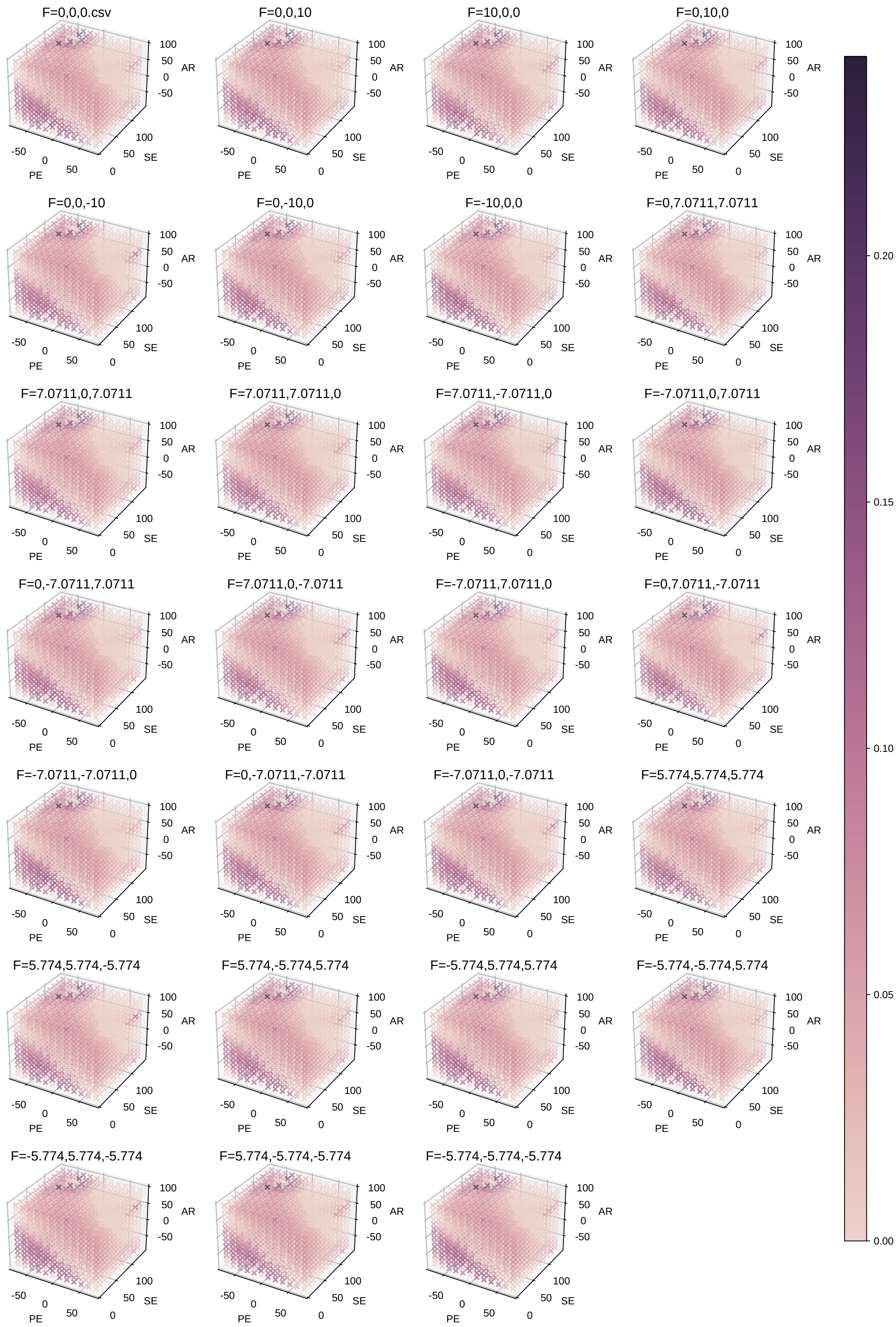

Fig. 15. Fatigue grid of the Infraspinatus under a force of 10 Newton.

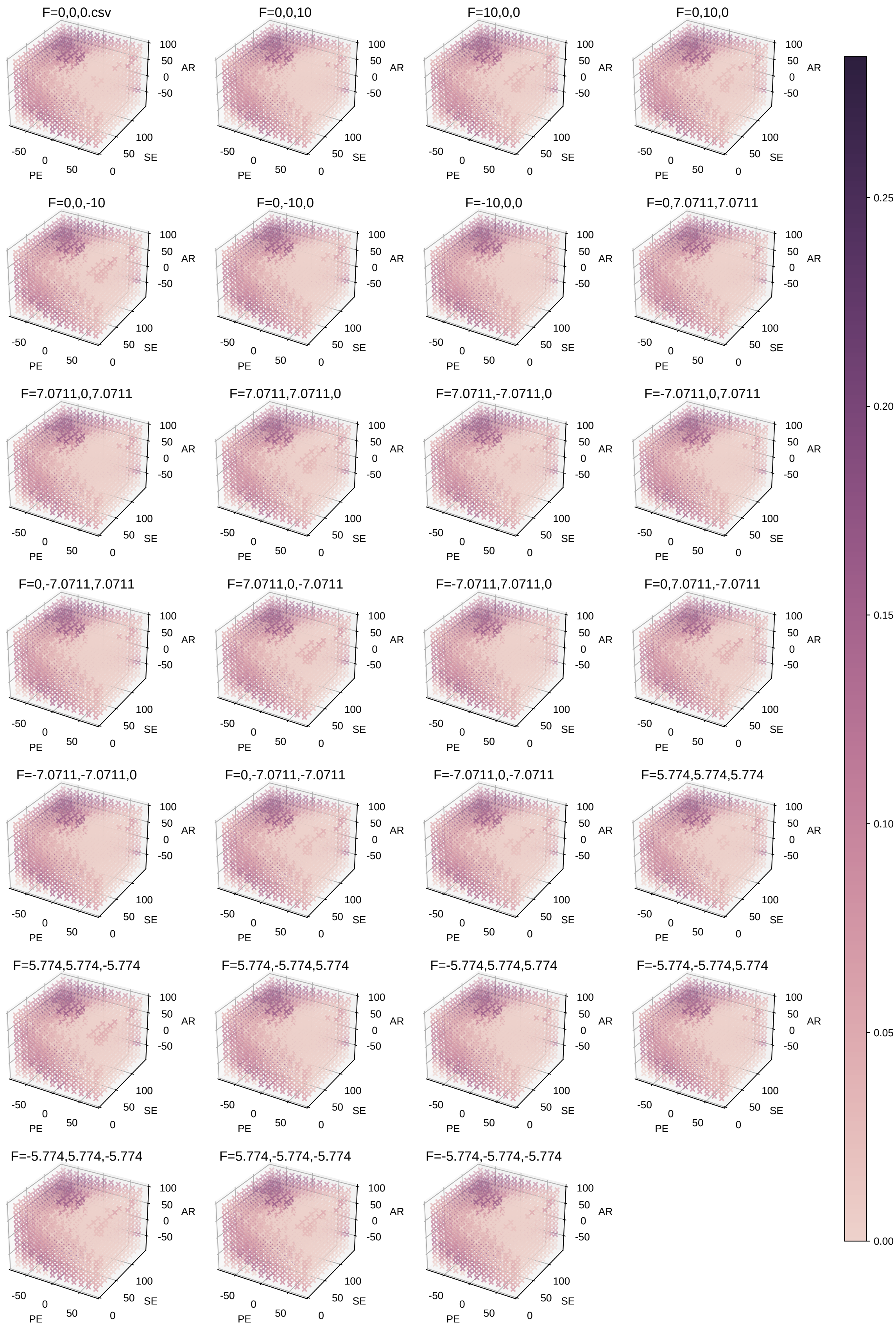

Fig. 16. Fatigue grid of the Supraspinatus under a force of 10 Newton.

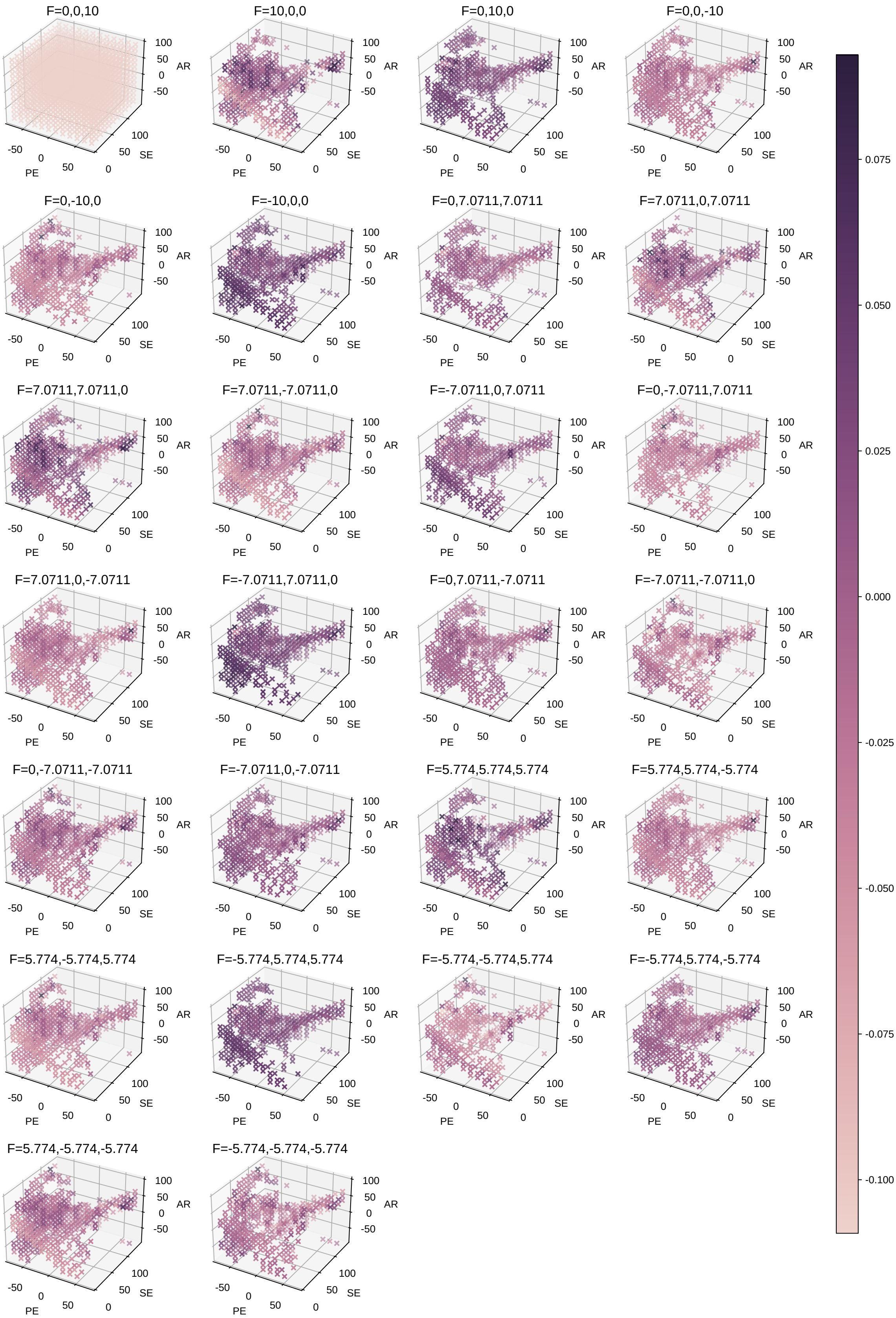

Fig. 17. Comparison Fatigue grid of the Infraspinatus under a force of 10 Newton against no force.

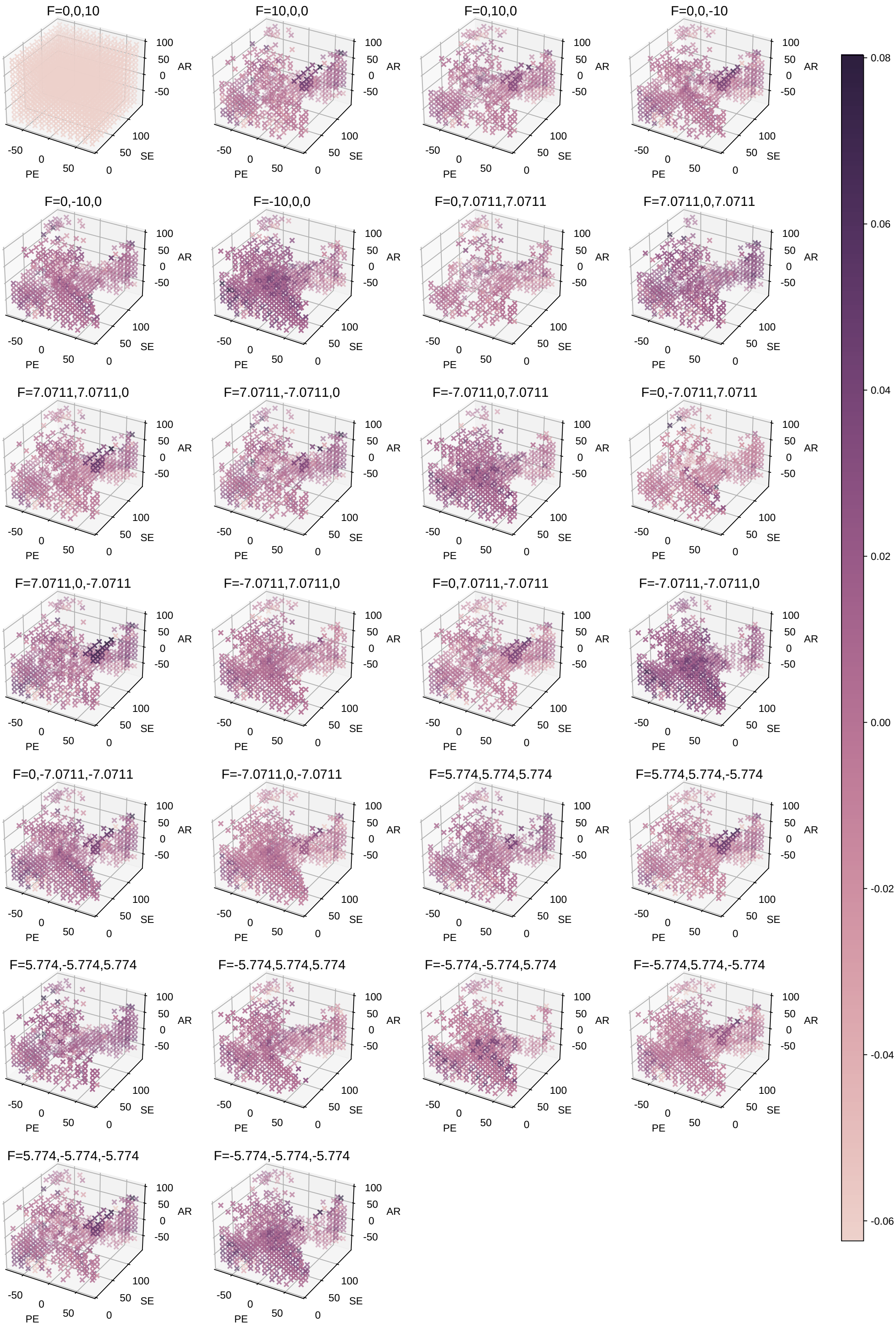

Fig. 18. Comparison Fatigue grid of the Supraspinatus under a force of 10 Newton against no force.

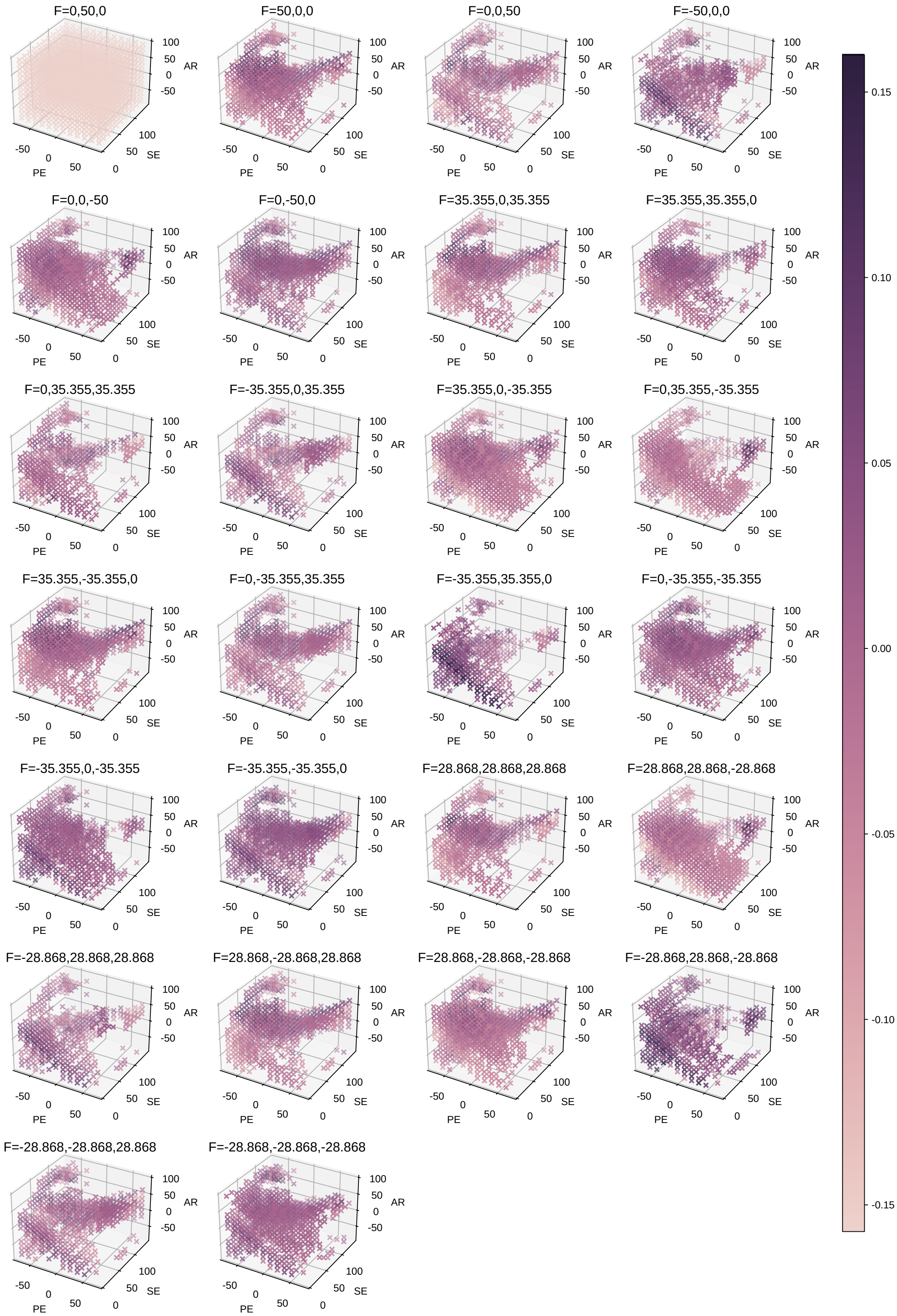

Fig. 19. Comparison Fatigue grid of the Infraspinatus under a force of 50 Newton against no force.

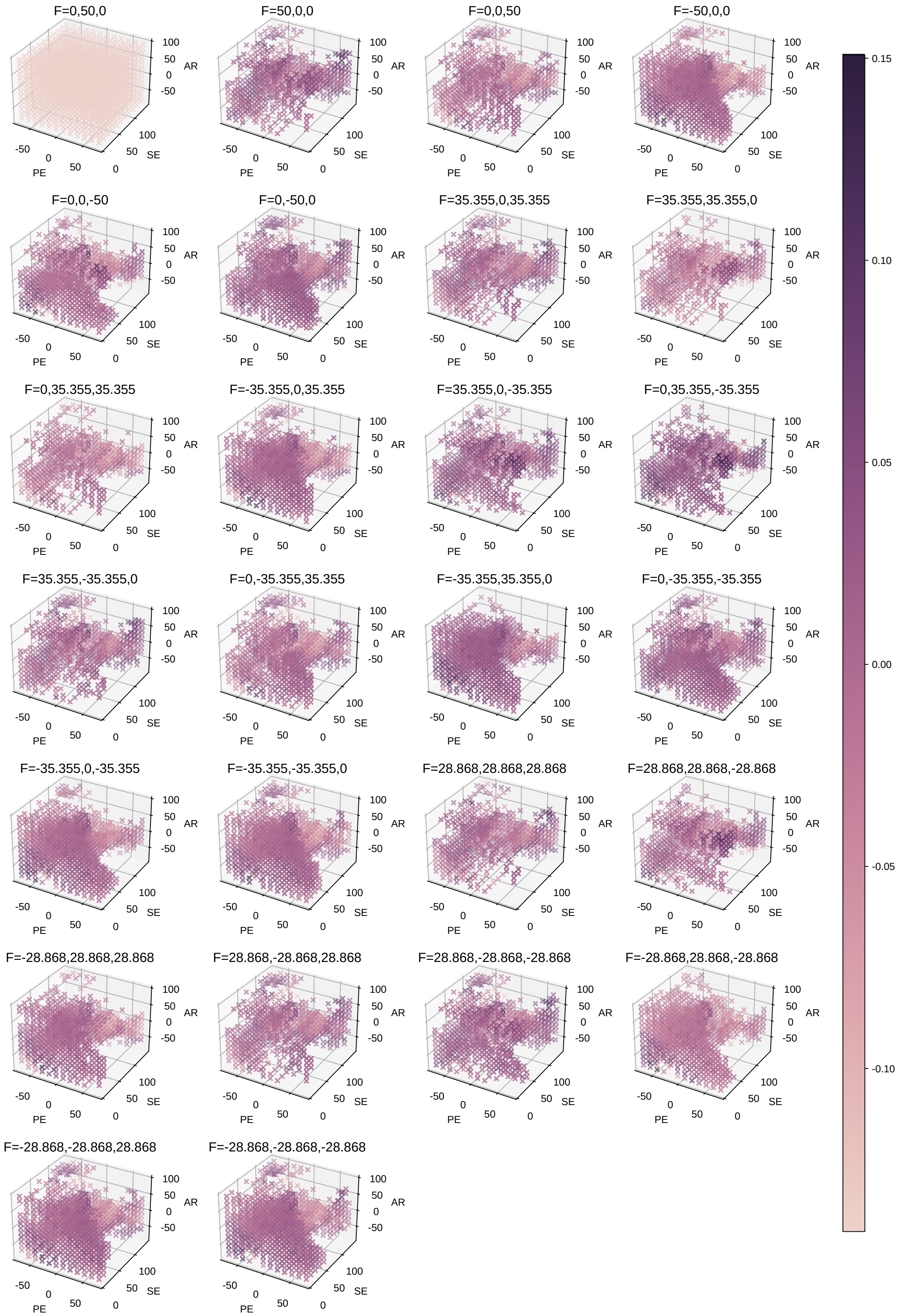

Fig. 20. Comparison Fatigue grid of the Supraspinatus under a force of 50 Newton against no force.

During the experiment, you will play a game with two versions.

Goal: Minimize the Overshoot

Controls: In the game, you are the blue dot, which lags behind the mouse to limit the speed at which you can move. You can change the background with the up and down arrow keys. The enemy is always visible. But the bonus point only appears when you are in the correct background layer. The upper right corner shows this information.

Rules:

Stay in the purple-colored areas.	Positive points
Prevent going into the black areas.	Negative points
Avoid enemy (red dot)	Negative points
Go to the bonus point (green larger dot)	Positive points

The two versions of the game:

Version zero: The background will change to show the areas where fatigue will build up as needed. So if you stay in the colored regions, especially the **lighter-colored areas**, the fatigue will build up properly. The bonus points will also only spawn in the colored sections.

Version one: You will control the fatigue. The second screen displays the current fatigue in the plot. The background will only change between layers. So, you will need to pay attention to the plots to see how the two muscle fatigues build up. The plots show the value the fatigue needs to reach and are color-linked. The blue line needs to end at the light blue line, and by staying in the darker areas, this line will increase more than the red line. The red line needs to end at the purplish line, and by staying in the lighter areas, the red line will increase more.

Cases:

You will play 3 cases of fatigue for both versions.

Version	Fatigue Muscle 1	Fatigue Muscle 2
0	0.2	0.2
1	0.2	0.2
0	0.45	0.2
1	0.45	0.2
0	0.2	0.45
1	0.2	0.45

You can get acquainted with both versions beforehand.

Fig. 21. The game explanation document that the participants had to read before the start of the experiment.

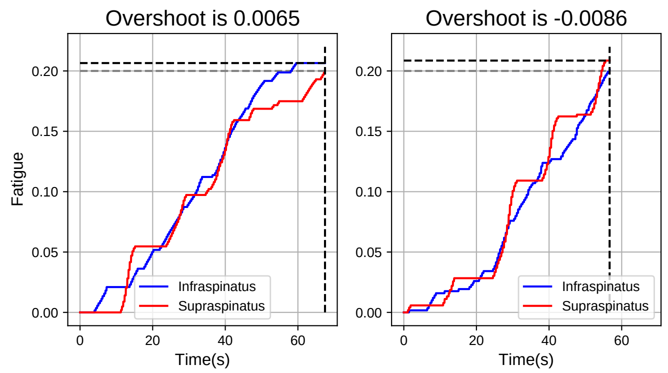

Fig. 22. Visual Example of the overshoot. The overshoot is measured as the maximum fatigue the muscles reach before or at the end of the game. With the recovery factor of the experiment, the muscles were not able to recover. So, only one of the muscles overshoots. The game ends when both muscles have crossed their desired fatigue level.

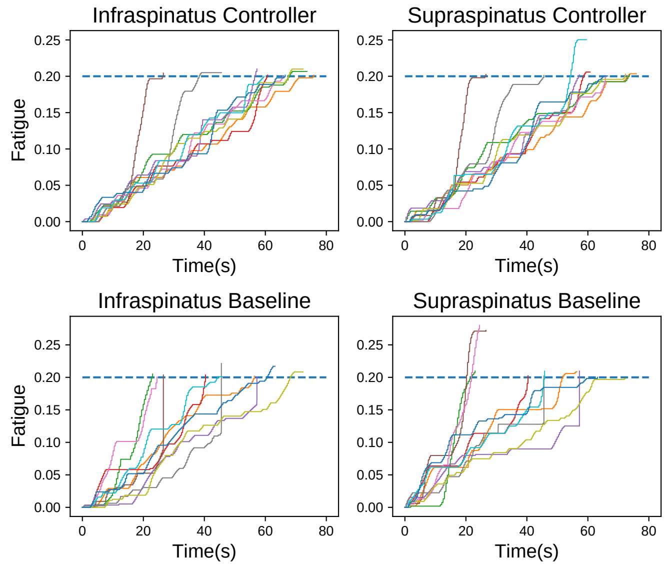

Fig. 23. The raw data of the fatigue for the two versions, where the desired fatigue was set to 20% for both infraspinatus and supraspinatus.

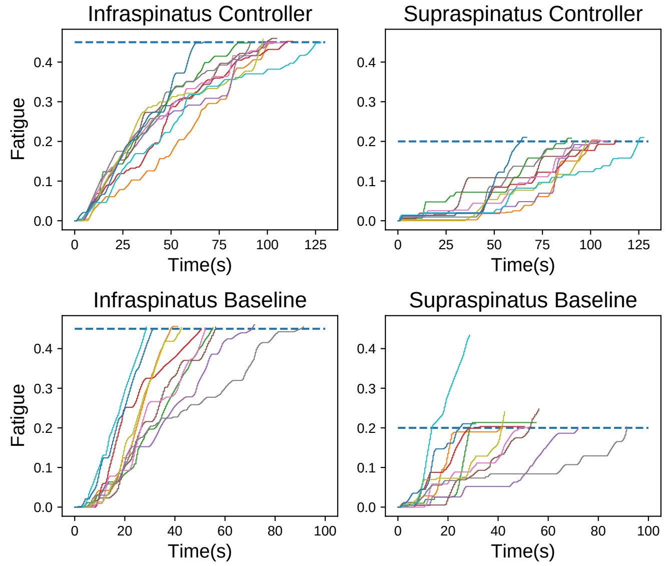

Fig. 24. The raw data of the fatigue for the two versions, where the desired fatigue was set to 45% for infraspinatus and 20% for supraspinatus.

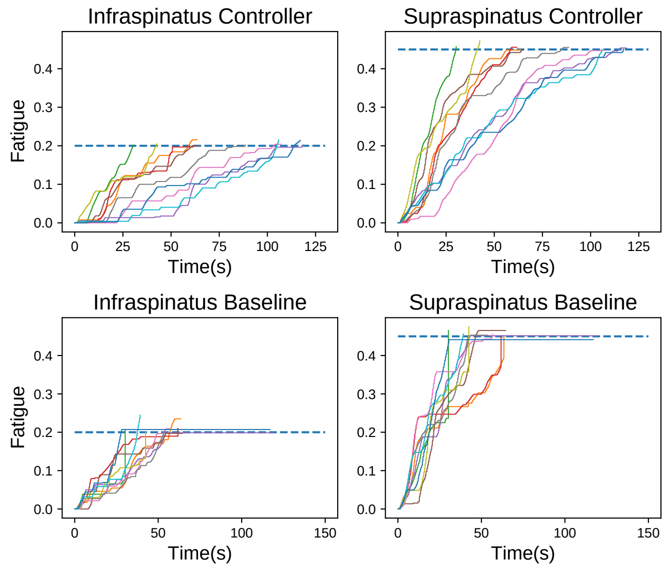

Fig. 25. The raw data of the fatigue for the two versions, where the desired fatigue was set to 20% for infraspinatus and 45% for supraspinatus.

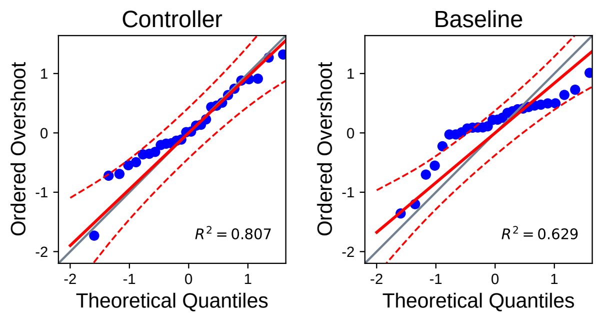

Fig. 26. The Quantile-Quantile plots of the overshoot showing that the data is mostly normally distributed for each version.

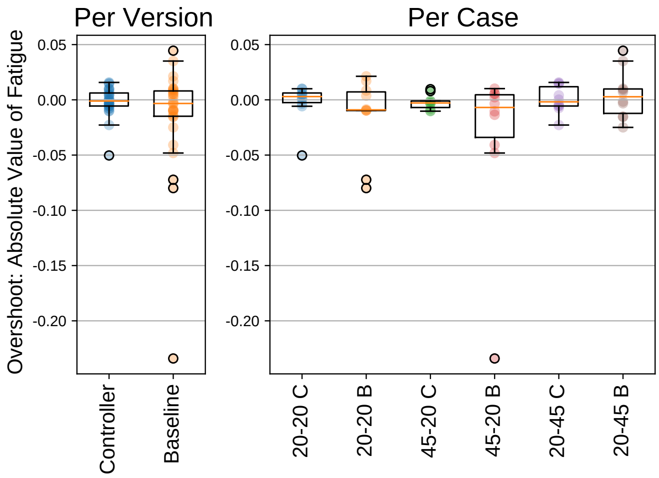

Fig. 27. On the left, the box plots for the combined controller cases and the box plot for the combined baseline cases. The overshoot mean of the controller and baseline is around zero. The variance is smaller for the controller than for the baseline. On the right, the box plot for each case for each version. The C stands for the controller, and the B for the baseline. The numbers indicate the desired fatigue percentage for each case, where the first value represents the infraspinatus and the second supraspinatus. The controller and baseline variances and means are similar for each case. The baseline variance is barely different.

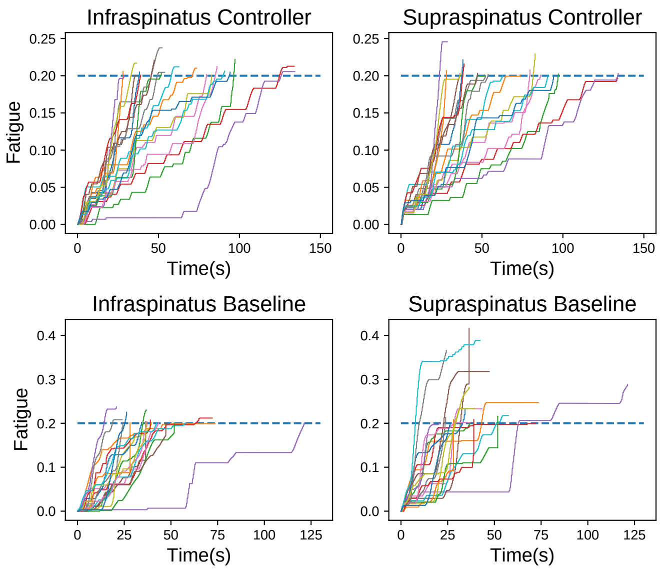

Fig. 28. The experiment raw data of the fatigue for the two versions, where the desired fatigue was set to 20% for both infraspinatus and supraspinatus. Each line in both plots in a row represents one game.

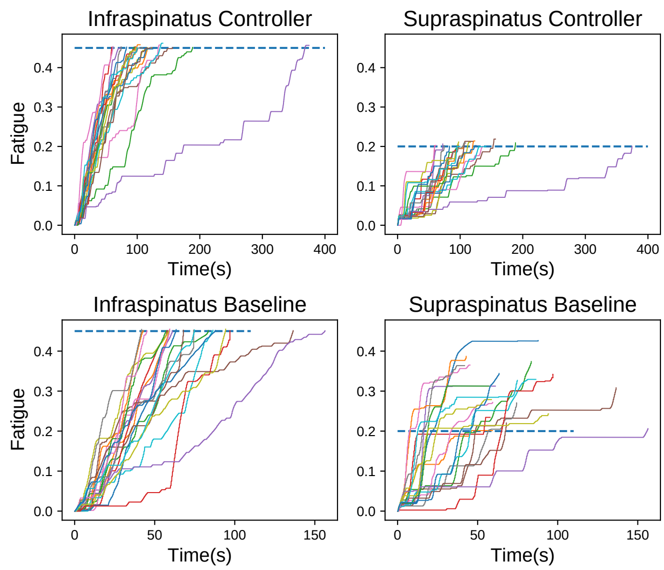

Fig. 29. The experiment raw data of the fatigue for the two versions, where the desired fatigue was set to 45% for infraspinatus and 20% for supraspinatus. Each line in both plots in a row represents one game.

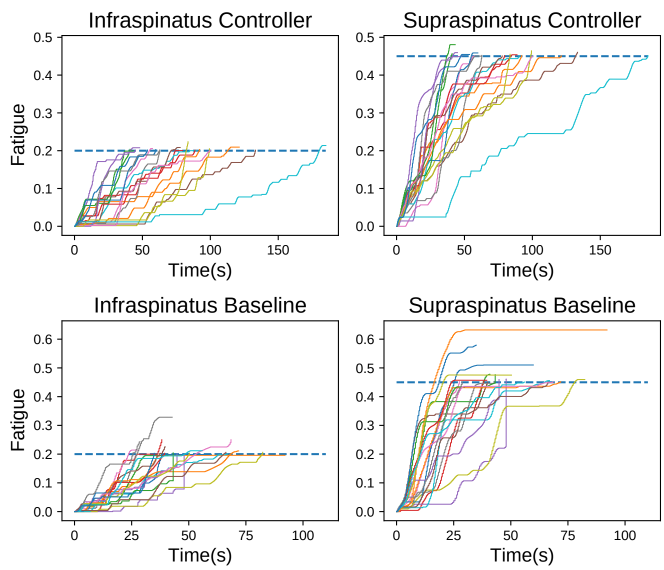

Fig. 30. The experiment raw data of the fatigue for the two versions, where the desired fatigue was set to 20% for infraspinatus and 45% for supraspinatus. Each line in both plots in a row represents one game.

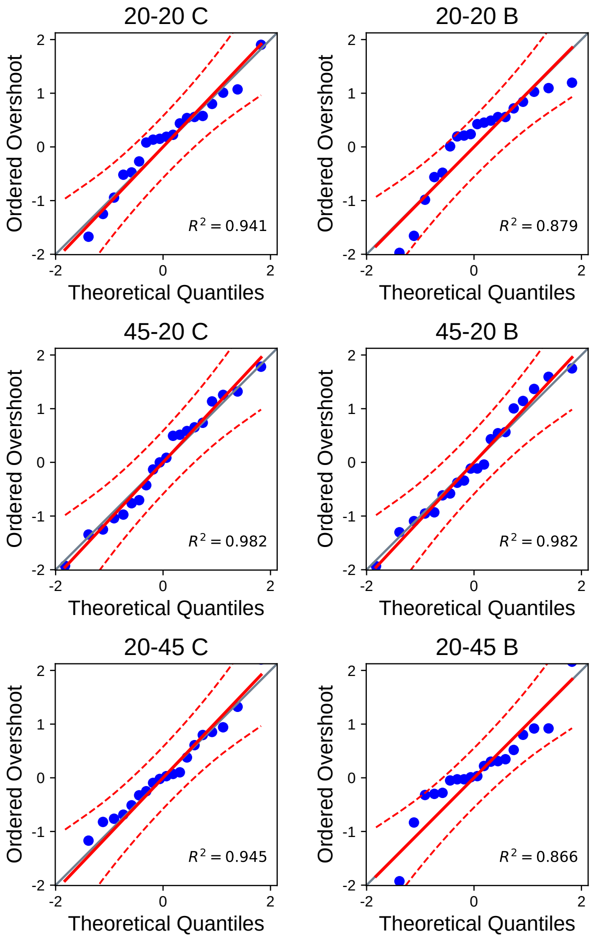

Fig. 31. The Quantile-Quantile plot of the overshoot showing that the data is normally distributed for each case and version.

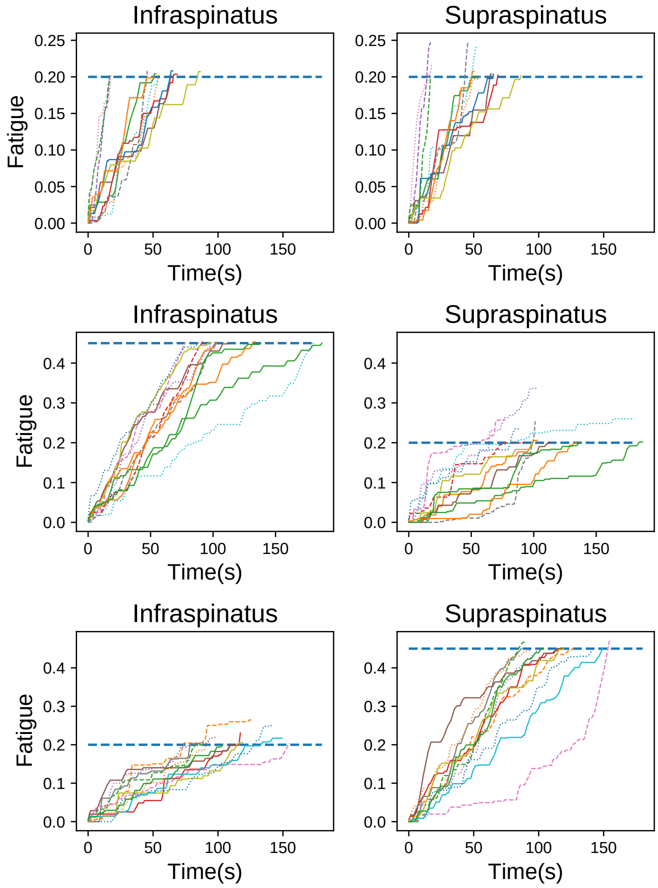

Fig. 32. The raw data of the fatigue for the controller version. Each row shows one of the fatigue cases. Each line in both plots represents one game. Different types of lines per person.

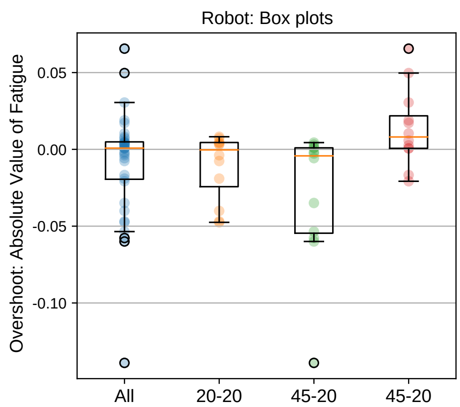

Fig. 33. The box plots of the overshoot of the robot demonstration. The games were all played with the controller.