Quantifying motor self-efficacy changes following motor interventions

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Abstract— Self-efficacy is crucial for the effective application of assistive technology and rehabilitation. This study proposes a novel approach to assess the impact of motor interventions on motor self-efficacy, relevant for human-robot interaction in rehabilitation, by focusing on the perceived reachable space. Twelve healthy adults underwent an arm movement restriction intervention using a robotic arm (KINARM), and changes in the perceived reachable space and muscle activity were measured before and after the intervention. The results indicated a reduction in the perceived reachable space and an adaptive decrease in muscle activity for unreachable targets following motor restriction. This suggests that the perceived reachable space can serve as an objective proxy for task-specific motor self-efficacy, which is valuable for evaluating user adaptation to robotic interfaces. Furthermore, these findings imply that in rehabilitation using interactive robots, a patient's effort levels may be influenced by their perception of task achievability.

I. INTRODUCTION

Self-efficacy, an individual's belief in their ability to perform tasks competently [1], is a critical factor in human interaction with technology, including assistive devices and rehabilitation robotics. This belief influences how individuals perceive their capabilities and persist through challenges, especially when using machines designed to aid function. In the context of motor activity and rehabilitation, motor self-efficacy significantly impacts recovery, adherence to interventions involving robotic systems, and long-term behavioral change. Traditional verbal ratings of self-efficacy may not fully capture the dynamic interaction between a user and a robotic system, highlighting the need for more objective measures that reflect the nuanced relationship between perceived ability and physical constraints.

In a previous study [2], we introduced the concept of "perceived reachable space"—the spatial region a person perceives as physically reachable—as a novel approach to assess motor self-efficacy. The brain's dynamic updating of reachable space based on experience, such as during tool use [4], suggests that it reflects not only biomechanical constraints but also a subjective sense of capability. This is particularly relevant to human-robot interaction, where a robotic interface can be perceived as an extension of the user's action capabilities. Therefore, perceived reachable space may serve as an indicator of motor self-efficacy and the perceived ability to effectively use an external device.

This approach may offer advantages over traditional methods. Unlike subjective questionnaires susceptible to bias, or performance metrics like success rates that only capture outcomes, perceived reachable space provides an objective measure of a user's perceived capability before an action is initiated. This pre-action focus aligns more closely with the core definition of self-efficacy [1] and holds promise for capturing its dynamic changes during human-robot interaction.

While physical limits affect self-efficacy, how these changes manifest during human-robot interaction and their objective quantification remain underexplored. This study thus investigates how motor self-efficacy, via perceived reachable space, changes with KINARM-imposed restrictions, simulating motor impairment or adaptation to an assistive robot. We aim to quantify the relationship between this restriction, perceived reachable space shifts, and concurrent EMG changes, reflecting the user's perceived capabilities while interacting with the robotic system. Understanding this dynamic interplay is key to designing robotic interfaces that are not only physically assistive but also psychologically attuned, thereby informing more effective, user-centered rehabilitation strategies.

II. METHOD

A. Participants

A total of 12 adults with no motor disabilities, aged 19 to 24 years (with a mean age of 21.58 and a standard deviation of 1.44), participated in this study. All participants received monetary compensation for their participation. Written informed consent was obtained from all participants in accordance with the study protocol approved by the Research Ethics Committee of The University of Tokyo (protocol number: 23-173). All procedures were performed in accordance with applicable guidelines and regulations.

B. Task and Apparatus

The task was two-dimensional arm reaching for the target on the display. Experiments were conducted

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using the Kinarm Exoskeleton Lab (Kinarm, Kingston, Ontario) and EMG measurement system (Cometa, Mini Wave Infinity). Participants were seated with each arm supported against gravity by plastic troughs attached to mechanical linkages that permit arm movements in the horizontal plane. Visual objects and feedback of hand position are displayed in the display while vision of the upper limbs was occluded with a physical barrier. The task program was created using MATLAB R2015aSP1 and Simulink (MathWorks Inc, Natick, MA, USA.).

C. Procedure

Display coordinates and joint angles of shoulder and elbow were defined as described in the Figure 1. Reach start target and goal target were displayed as circles with a radius of 1 cm. The center of start position was $(0.2, 0.2)$, that of goal position were randomly chosen from 20 positions which were placed on the centerline $x = 0$ at 2 cm-intervals, that is, $(0, 0.16), (0, 0.18), ..., (0, 0.54)$. Each 20 positions of targets were equally displayed in every set.

The task protocol consists of four sets: training 1 (200 trials), test 1 (100 trials), training 2 (200 trials), and test 2 (100 trials). In training sets, participants were required to reach their hand to the displayed target and make maximum efforts to reach if the target cannot be reached due to the arm length (not to give up reaching). In test sets, participants were required to answer whether or not they thought they could reach the displayed target and its confidence as 0-100 % by reaching the cursor to either Yes or No cue and then crossing the bar between 0 $(0.1, 0.3)$ and 100 $(0.3, 0.3)$ without reaching to the goal target. The positions of Yes and No cue $((0.15, 0.25), (0.25, 0.25))$ are randomized between participants. In training 1, participants could freely move their arm (that is, shoulder and elbow joints). In training 2, participants could not fully extend their arm so that the elbow joint angles θ_e were constrained to $\theta_e > 75°$ ($\theta_e = 0°$ corresponded to full extension). In both test 1 and test 2, arm movements were not physically constrained, and participants were instructed to answer based on their judgment at that time.

EMG was also used to record the muscle activity of biceps and triceps during movements. EMG data was synchronized according to the TTL pulse signals exported from KINARM when each trials started.

D. Data analysis

For the test sets, the perceived reachability rate (i.e., the proportion of trials in which participants judged the target as reachable by responding "YES"), confidence, and reaction time were calculated for each of the 20 target conditions. The results of Test 1 and Test 2 were statistically analyzed using a two-way repeated-measures analysis of variance (ANOVA), with test set (Test 1 vs. Test 2) and target condition as within-subject factors.

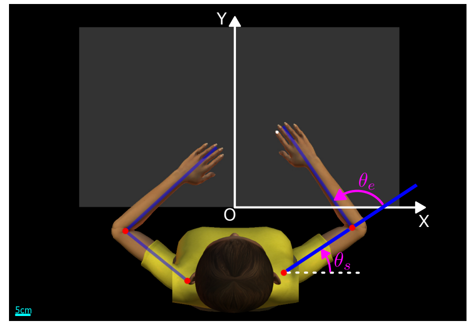

Fig. 1. The display coordinates and the joint angles.

To evaluate the changes in parameters around the boundary between reachable and unreachable conditions across all participants, target conditions were adjusted for each participant so that the condition where the participant was able to reach the target at least once in training 1 was set to condition 0. The perceived reachability rate (y_1), confidence (y_2), and reaction time (y_3) for each participant as well as the average across all participants were calculated for the adjusted condition (x) and fitted to the function as follows respectively:

$$y_1 = a(1 + \exp(-b(x - c)))^{-1} \tag{1}$$

$$y_2 = a \exp(-((x - b)^2/(2c^2))) + 1 \tag{2}$$

$$y_3 = a \exp(-((x - b)^2/(2c^2))) + d \tag{3}$$

Here, a, b, c, d were the fitting parameters to estimate. To test whether the shapes of the fitting curves differed between Test 1 and Test 2, different parameters were extracted for each dependent measure. For the perceived reachability rate, the point of subjective equality (PSE) and the interval of uncertainty (IU) were calculated from each participant's fitted curve. For confidence and reaction time, the peak amplitude (maximum y-value) and kurtosis of the fitted curve were computed as indices of central tendency and sharpness, respectively. These parameters were statistically compared between Test 1 and Test 2 using paired t-tests.

Signal processing steps were implemented to reduce noise in the raw EMG data from Training 1 and 2 [3]. The raw data were first filtered using a 20-450 Hz fourth-order band-pass Butterworth filter, then normalized, and subsequently filtered using a 3 Hz low-pass filter.

III. RESULT

A. Behaviour

For the behavioral data, separate two-way analyses of variance (ANOVA) with factors test condition (2 levels) and target position (20 levels) were conducted for the means of the perceived reachability rate, confidence, and reaction time. Perceived reachability rate showed significant main effects for both factors ($F(1, 11) = 108.9, p < .001, \eta_p^2 = .91$ and $F(19, 209) = 70.87, p < .001, \eta_p^2 = .87$, , respectively) and a significant interaction ($F(19, 209) = 5.01, p < .001, \eta_p^2 = .31$). For confidence and reaction time, the main effect of test condition was not significant ($Fs < .05, n.s., \eta_p^2 < .01$), while the main effect of target position was significant (confidence: $F(19, 209) = 3.73, p < .01, \eta_p^2 = .25$; reaction time: $F(19, 209) = 2.09, p < .01, \eta_p^2 = .16$). Crucially, a significant interaction between test condition and target position was observed for both confidence ($F(19, 209) = 3.36, p < .001, \eta_p^2 = .23$) and reaction time ($F(19, 209) = 3.25, p < .001, \eta_p^2 = .22$). Further details of these interactions will be discussed in conjunction with the fitting analysis results.

The means of the perceived reachability rate, confidence, and reaction time, along with their fitted curves for the adjusted condition, are shown in Figure 2. As seen in the figure, the shapes of the fitted curves in Test 1 and Test 2 appear highly similar. Statistical analyses confirmed that there were no significant differences between Test 1 and Test 2 for any of the fitted parameters. Specifically, for the perceived reachability rate, both PSE (t[11]=0.48,p=0.64) and IU (t[11]=1.49,p=0.16) did not differ significantly. Likewise, for confidence, neither the peak amplitude (t[11]=0.30,p=0.76) nor the kurtosis (t[11]=0.81,p=0.44) showed significant differences. For reaction time, both the peak amplitude (t[11]=0.87,p=0.40) and kurtosis (t[11]=0.15,p=0.88) also remained statistically unchanged across tests. These results indicate that the shapes of the fitted curves were preserved between Test 1 and Test 2. In other words, the change from one curve to the other can be interpreted as a translational shift, rather than a change in form.

B. Muscle Activities

To investigate whether the perceived reachable space changed depending on the presence or absence of movement restriction, we examined differences in muscle activity between Training 1 and Training 2. Targets were categorized into three conditions based on reachability: reached in both Training 1 and 2 (Reach-Reach condition), reached in Training 1 but not in Training 2 (Reach-No condition), and not reached in either Training 1 or 2 (No-No condition). We compared muscle activity across these conditions between the two training sessions. To control for muscle activity levels across trials, we calculated the activity from the start of each trial until the mean reaction time for that specific trial.

A three-way within-subjects analysis of variance (ANOVA) with factors of muscle (Biceps, Triceps), Training (Training 1, Training 2), and Condition (Reach-Reach, Reach-No, No-No) was conducted on the muscle activity data. The results showed that the three-way interaction was not significant ($F(2, 22) = .33, n.s., \eta_p^2 = .03$). However, the interaction between Training and Condition was significant ($F(2, 22) = 3.78, p = .039, \eta^2 p = .26$). The results for the Training and Condition factors are illustrated in Fig. 3. Further analysis of simple main effects revealed a significant main effect of Training within the No-No condition ($F(1, 11) = 6.01, p = .03, \eta^2 p = .35$), indicating that muscle activity was significantly greater during Training 1 compared to Training 2 when the target was not reached in either session. This result suggests that motor function was reduced in Training 2, likely due to the movement restriction imposed during that condition.

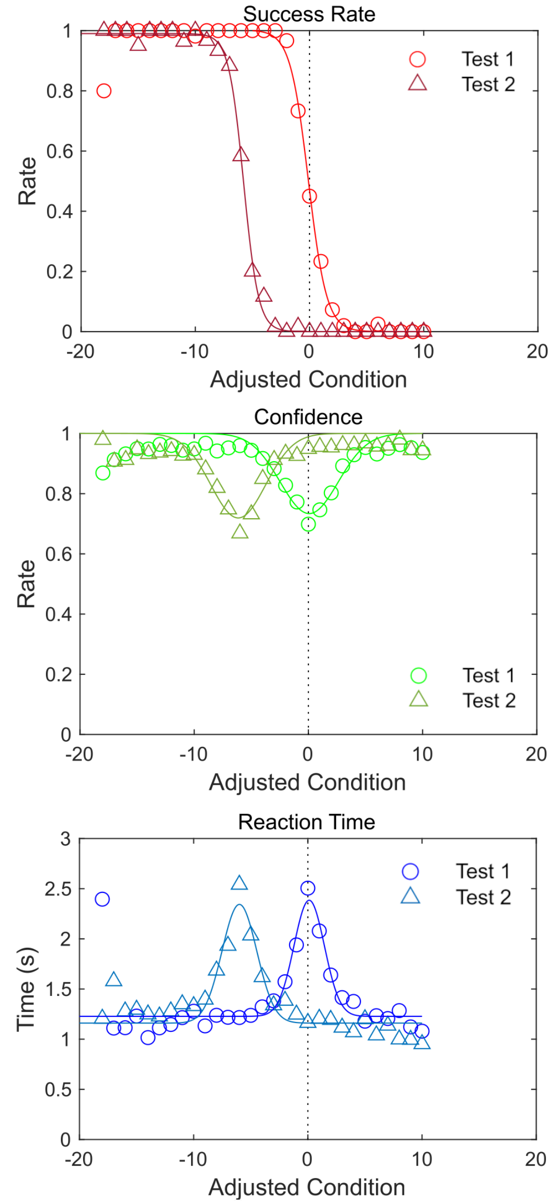

Fig. 2. The mean of the perceived reachability rate (top), confidence (middle), and reaction time (bottom) with fitting curve for adjusted condition.

IV. DISCUSSION

The key behavioral finding is the significant change in participants' reachability judgments following robot-induced movement restriction, relevant to understanding user adaptation to robotic interfaces. While fitted curves for perceived reachability rate, confidence, and reaction time retained their overall shapes between Test 1 and Test 2 (no significant differences in PSE, IU, peak amplitude, or kurtosis), the entire curve shifted, making

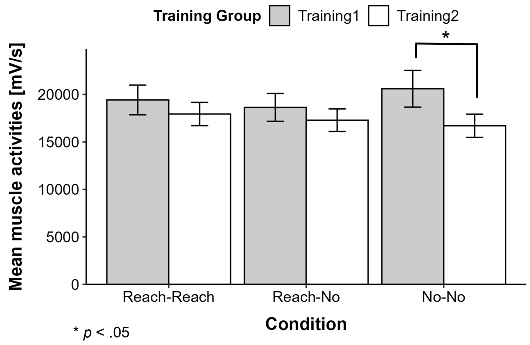

Fig. 3. Mean muscle activities for each condition. Error bars represent standard errors (SE).

nearer targets more likely to be judged reachable. This pattern suggests a reduction in perceived reachable space after Training 2, which involved robot-mediated arm movement restriction. It is plausible that such shrinkage likely reflects a decline in motor self-efficacy from experiencing movement limitation, particularly when interacting with a system that alters perceived action capabilities.

Furthermore, a key finding was the significant reduction in muscle activity specifically in the No–No condition during Training 2 compared to Training 1. In this condition, targets were unreachable in both sessions, but the robot-imposed restriction in Training 2 made this impossibility more apparent. When effort is a cost and reaching a target a potential reward, investing effort becomes economically unfavorable if the probability of success is clearly zero [5], a situation reinforced by the robotic system's constraints. Therefore, reduced muscle activity in Training 2 could be interpreted as an adaptive strategy to conserve energy and time when the goal, informed by interaction with the robot, is perceived as definitively unattainable—a biologically rational decision to minimize wasted effort. This adaptive reduction in effort was specific to the No–No condition, suggesting that individuals are sensitive to the certainty of failure, particularly when feedback is machine-mediated, and modulate their effort accordingly.

In contrast, the Reach–No condition did not show a significant change in muscle activity. It is possible that prior success in Training 1 helped maintain participants' belief in the potential achievability of the task, resulting in continued effort even after the restriction. This pattern suggests that effort modulation is not uniform but is closely related to one's prior experience with the task, further linking perceived achievability and motor engagement. Together, these findings indicate that such adjustments reflect a targeted evaluation of task feasibility within the human-robot system, rather than a generalized response to physical constraint. This adaptive modulation of effort may parallel how users learn to interact with assistive or rehabilitative robots.

While general fatigue may have played a role in the decrease in muscle activity, it is less likely to be the primary driver. The effect was significant only in the No-No condition, and no significant general decline in confidence or increase in reaction time was observed from Test 1 to Test 2. This pattern suggests that the findings are more plausibly explained by a targeted decline in motor self-efficacy following the movement restriction, in addition to any potential effects of generalized fatigue.

Our findings have important implications for robotic rehabilitation, suggesting that interfaces should provide feedback that cultivates realistic self-efficacy to optimize patient engagement and recovery outcomes. Nevertheless, this study has several limitations. First, to fully rule out the influence of fatigue or habituation, future studies should include a control group that passively experiences the robot-imposed restriction in Training 2 without actively performing movements. This comparison would help clarify whether the observed effects truly reflect changes in motor self-efficacy rather than nonspecific factors. Second, as our sample consisted solely of healthy young adults, the generalizability of the findings is limited. Future work should incorporate appropriate control conditions and more diverse samples to confirm and extend these conclusions.

V. CONCLUSIONS

This study suggested that a robotic exoskeleton manipulating reaching ability changes the perceived reachable space, highlighting its potential as an objective proxy for task-specific motor self-efficacy. The findings may be particularly relevant for evaluating user adaptation to robotic interfaces in rehabilitation. This approach may offer a quantitative alternative to self-reports, potentially advancing the understanding and assessment of self-efficacy dynamics in human-robot interaction and could contribute to the future development of more effectively tailored, user-centered robotic interventions.

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