A usability study on mobile EMG-guided wrist extension training in subacute stroke patients—MyoGuide

Hao-Ping Lin (haoping.lin@sec.ethz.ch)
Singapore-ETH Centre, Future Health Technologies Programme

Yang Xu
Department of Rehabilitation, Shengjing Hospital of China Medical University

Xue Zhang
Department of Health Sciences and Technology, Neural Control of Movement Laboratory, ETH Zurich

Daniel Woolley
Department of Health Sciences and Technology, Neural Control of Movement Laboratory, ETH Zurich

Lina Zhao
Department of Rehabilitation, Shengjing Hospital of China Medical University

Weidi Liang
Department of Rehabilitation, Shengjing Hospital of China Medical University

Mengdi Huang
Department of Rehabilitation, Shengjing Hospital of China Medical University

Hsiao-ju Cheng
Singapore-ETH Centre, Future Health Technologies Programme

Lixin Zhang
Department of Rehabilitation, Shengjing Hospital of China Medical University

Nicole Wenderoth
Department of Health Sciences and Technology, Neural Control of Movement Laboratory, ETH Zurich

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Abstract

Background: Effective stroke rehabilitation requires high-dose, repetitive-task training, especially during the early recovery phase. However, the usability of upper-limb rehabilitation technology in acute and sub-acute stroke survivors remains relatively unexplored. In this study, we introduce sub-acute stroke survivors to the “MyoGuide”, a mobile training platform that employs surface electromyography (sEMG)-guided neurofeedback training for post-stroke wrist extension. Notably, the study places a strong emphasis on evaluating the platform’s usability within clinical contexts.

Methods: We report the results of seven sub-acute post-stroke participants. The MyoGuide mobile training platform provided participants with real-time feedback, gamification features, and user control. Participants underwent wrist extension training, which encompassed calibration, stability assessment, and dynamic tasks. The training was conducted in supervised 1:1 sessions, spanning ten days. All training records were recorded within the application, usability was assessed through System Usability Scale (SUS) and a questionnaire administered during the final session. Daily written reports were provided by the therapist throughout the study duration.

Results: The usability analysis yielded positive results, with a median SUS score of 82.5. Across the training sessions, patients progressed as indicated by significant increases in both the Stability Assessment Scores and the Level of Difficulty (LoD) that could be achieved in the dynamic task. The rate of progression differed based on initial impairment levels of the patient. During the training sessions, therapists documented not only the day-to-day performance of participants but also the extent of support required, particularly for those with lower baseline motor function. In parallel, participants who had experienced stroke expressed a keen interest in continuing home-based training. However, they also acknowledged challenges related to independently using the Myo armband and software.

Conclusions: This study introduces the MyoGuide training platform and demonstrates its usability in a clinical setting for stroke rehabilitation, with the assistance of a therapist. The findings support the potential of MyoGuide for wrist extension training in patients across a wide range of impairment levels. However, certain usability challenges, such as donning/doffing the armband and navigating the application, need to be addressed to enable independent MyoGuide training requiring only minimal supervision by a therapist.

Background

Stroke is the third leading cause of disability worldwide [1]. At least 50% of stroke survivors suffer from upper limb impairments that limit engagement in activities of daily living (ADLs) and reduced quality of life [2, 3]. There is a consensus that effective post-stroke upper limb rehabilitation benefits from high-dose, repetitive-task training [4, 5]. Nonetheless, ensuring the delivery of sufficient training doses remains challenging, especially during the acute to subacute phases [6–10]. Additionally, it’s essential to emphasize the significant impact of treatment timing on post-stroke motor recovery. Research has shown
that the optimal rehabilitation period occurs within the first 60 to 90 days following a stroke [11]. Furthermore, clinical trials on human subjects have consistently revealed that individuals receiving early intervention exhibit significant better motor recovery outcomes compared to those who received delayed intervention [12–14]. Therefore, new technologies that promote high-dose upper limb rehabilitation during the early stages of stroke, even when the upper limb is still significantly weakened and unable to generate overt movements, may serve as a beneficial supplement to conventional treatment methods.

In this study, we present "MyoGuide", a mobile platform utilizing surface electromyography (sEMG) guided neurofeedback training for post-stroke wrist extension training. sEMG is a widely used technique for real-time biofeedback, mainly due to it being non-invasive and easy to use [15]. It also enables the detection of movement intention even when the upper limb is paretic [16, 17]. Such capability is vital for stroke patients with limited active movement. Prior studies have used sEMG biofeedback in the context of gait training [18, 19] and upper limb training with several advantages, including the mitigation of co-contraction pattern [20], enhanced functional recovery outcomes when compared with conventional therapy [21, 22], and good usability from the end-users [23]. Our current focus is on wrist extension training, which is pivotal for both ADLs [24, 25] and hand grasping actions [26, 27]. Wrist extension ability has also been highlighted as a potential indicator of upper limb functional recovery [28].

Recently, mobile therapy devices like portable virtual reality [29] and mobile training setups [30] have emerged as innovative interventions, potentially improving post-stroke outcomes including independence [29–31], cognition [32], and fine motor skills [33–35]. These mobile solutions provide accessibility, flexible training options, scalability, and affordability [36]. Incorporating gamification further enhances training, particularly when increasing dose through repetition is required [37, 38]. However, it is worth noting that previous studies focusing on mobile-based stroke rehabilitation have predominantly targeted chronic survivors [39–41], while far less research has been conducted during the early recovery phase. The usability of upper-limb rehabilitation technology for non-chronic survivors remains relatively unexplored. To effectively pinpoint and address usability challenges, a rigorous and iterative evaluation process is required [42–44]. Previous studies have shown that inclusive participation of both patients and therapists has played a pivotal role in shaping the development of wearable exoskeletons [45, 46] and interactive game-based virtual reality systems [47].

Our primary objective here is to integrate usability evaluations into the early development phase of MyoGuide. Further, we aim to obtain first feedback from therapists as to whether they can effectively employ it in their rehabilitation practices and validate MyoGuide's suitability for integration into clinical settings.

Methods

Participants
Our study participants were recruited at the Rehabilitation Centre at the Shengjing Hospital of China Medical University in Shenyang, Liaoning, China. To be included in the study, participants needed to meet certain criteria: (1) having experienced a mono-hemispheric, ischemic, or hemorrhagic stroke, (2) demonstrating measurable EMG activity in the m. extensor carpi radialis (ECR) of the affected arm, (3) having had a stroke between 2 weeks and 6 months prior to study inclusion, and (4) being older than 18 years of age. The exclusion criteria are: (1) having fully recovered wrist function (FMA-UE wrist component = 10), (2) experiencing enhanced spasticity (MAS > 2), (3) having severe impaired vision or blindness, (4) exhibiting visuospatial neglect, (5) suffering from complete somatosensory loss, (6) having cognitive or communication impairment, or (7) having conditions that prevent informed consent or compliance.

Ten participants were recruited in the study. However, due to technical issues during data transfer, we lost data from two participants. Additionally, one participant withdrew from the study due to a personal schedule change. Consequently, a total of seven participants successfully completed the training and provided comprehensive responses to the usability questionnaires.

**MyoGuide Mobile Training Platform**

The training platform consists of an eight-channel sEMG sensor, the Myo armband (Thalmic Labs, Ontario, Canada, Fig. 1a), with an in-house developed application that can be run on a mobile device such as a tablet or phone. The application provides a series of training blocks that were predefined by an experienced therapist. In a training session, the participant can log in with an identification code and manually start the exercises. To maximize the user experience and engagement in using the device, we also implemented real-time feedback (e.g., avatar being controlled by sEMG activity, or scores shown on the screen), gamification and user control freedom (e.g., the training can be interrupted or stopped by the user).

**Experimental Protocol**

The experiment protocol was conducted with a therapist-to-patient ratio of 1:1 in a supervised setting. The Myo armband was positioned on the stroke affected forearm. Its purpose was to capture the sEMG signals originating from the forearm muscles, particularly the ECR muscle. The sEMG sensor featuring the LED icon was placed directly over the ECR muscle belly. A tablet was positioned in front of each participant on a table, serving as a display for the experimental tasks. Participants were seated in a comfortable manner, and arm support was provided when needed. The upper extremity neurofeedback training sessions, guided by sEMG signals, consisted of three distinct tasks: sEMG calibration, a stability assessment, and a dynamic task (as shown in Fig. 1a).

During the **calibration task**, participants were given instructions to perform a maximal voluntary contraction of the ECR muscle and hold the position for a minimum of one second. In Fig. 1a, the second subplot displays eight bars representing the sEMG channels. Among the middle four green-colored channels (which generally represent the electrodes placed over the extensors), the channel with the
highest sEMG range (max sEMG - min sEMG) is identified as the "extensor channel" for performing the stability assessment and dynamic task.

After the calibration process a **stability assessment** was performed (depicted in the third subplot of Fig. 1a). The purpose of this assessment was to gauge the participants’ ability to regulate wrist extensor (ECR) sEMG activity using the extensor sEMG channel selected during calibration. To represent the participants’ sEMG activity level, a yellow cursor was employed, which moved to the right as the sEMG activity increased. During the stability assessment, participants were tasked with manipulating the cursor on the screen and keeping it within a target circle. They achieved this by actively controlling the sEMG level of their wrist extensors. The objective was to hold the cursor within the target area for a duration of three seconds. Each trial's score depended on how long the cursor remained within the target area, with a maximum score of 100 indicating that the cursor remained within the target circle for the entire duration. After completing a trial, participants were instructed to relax their wrist extensors and return the cursor to its starting position.

The stability assessment included three target areas, each associated with a specific calibrated maximum EMG level (25%, 50%, and 75%). The order of presentation for these target areas was randomized. Each assessment session comprised a total of 15 trials, with 5 repetitions allocated to each target area. The participants' proficiency in static sEMG control was evaluated based on the summed assessment score across all trials. The maximum attainable score was 1500, serving as an indicator of their overall performance and mastery of static sEMG control during the assessment.

In the **dynamic task**, presented in Fig. 1a, participants were assigned the objective of controlling a panda avatar by modulating their wrist extensor sEMG signals. The vertical and horizontal position of the panda avatar corresponded to the recorded sEMG level from the extensor channel, meaning that higher EMG signals led to the panda flying higher and faster. This task incorporated gamification elements, where participants were required to guide the panda towards rewarding coins placed at various heights while avoiding wall obstacles.

The task's level of difficulty (LoD) ranged from 1 to 100, gradually increasing to challenge participants' dynamic control over their extensor sEMG activity. To enhance the training tasks, several elements were adjusted to modulate LoD. These adjustments included decreasing the distance between obstacles, necessitating participants to engage in more frequent and rapid muscle contractions and relaxations. Additionally, the height of obstacles was raised, demanding greater muscle activation to prevent collisions with the walls.

The LoD was dynamically adapted based on participants' performance of the previous trial, considering factors such as the number of coins collected, and the distance traveled. A predefined threshold was set at 50% of the maximum achievable coins and distance, and if participants' performance exceeded this threshold, the LoD was increased to provide a higher level of challenge. Conversely, if their performance fell below the threshold, the LoD was decreased to ensure an appropriate level of challenge. This adaptive
approach allowed for personalized adjustments, aiming to maintain an optimal level of challenge and foster continuous improvement throughout training.

The dynamic training sessions were structured in the following manner: Each training block, as shown in Fig. 1b, had a duration of 2 minutes, followed by a 30-second break. Participants completed five consecutive blocks on each of the 10 training days. On the final day of training, participants were asked to provide feedback on the usability of the system through questionnaires, allowing for an evaluation of their overall experience. During the training sessions, the therapist played a crucial role by closely observing the participants and documenting their observations, as depicted in Fig. 1c. This qualitative data collection provided valuable insights into participants' performance, engagement, and overall experience during the training sessions. The entire intervention was conducted over a span of two weeks, with training sessions scheduled five days per week. This schedule resulted in a total of 10 sessions for each participant.

**Outcome Measures**

**Primary outcome: System Usability Scale**

We specifically focused on evaluating the usability of our MyoGuide mobile training platform using the widely recognized System Usability Scale (SUS) [48]. The SUS questionnaire consists of ten items and is designed to assess the overall usability, including effectiveness, efficiency, and satisfaction, of a system. Participants rate their responses on a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). To calculate the total SUS score, two separate calculations are performed. Firstly, the sum of the responses to the odd-numbered questions is subtracted by 5. Secondly, the sum of the responses to the even-numbered questions is subtracted from 25. These two results are then combined and multiplied by 2.5, resulting in the final total SUS score. The scores range from 0 to 100, with higher scores indicating better usability. Based on the adjective rating scale provided in [49], the interpretation of the total SUS score falls within different categories of overall usability. A score between 51 and 71 is considered "OK", a score between 72 to 85 is considered "Good", a score between 86 to 91 is considered "Excellent", and a score between 92 to 100 is considered "Best imaginable". This evaluation was undertaken with seven sub-acute stroke survivors.

**Secondary outcome: Possibility of training at home, training components and therapist’s feedback**

In addition to the SUS questionnaire, we designed a supplementary survey to assess participants' willingness to continue training at home, their overall attitude towards the system, and their confidence in independently using the device. This survey consisted of six items rated on a 5-point Likert scale, providing insights into participants' perceptions and experiences with MyoGuide. Moreover, a comprehensive monitoring of various training components was conducted throughout the intervention period. The application employed in the study tracked participants' stability assessment scores and the
LoD during the dynamic task to effectively evaluate their aptitude for advancing within the training program. Additionally, the therapist documented observations in a training survey, encompassing critical details such as the provision of assistance, the participant's positioning during training sessions, and general observations. This feedback proved important in understanding the participants' training experience, as well as providing further insights into their overall progress and level of engagement.

**Data Analyses**

To assess the temporal evolution of assessment scores and LoD, a linear-mixed effects model was employed using the lme4 package in R [50, 51]. This modeling approach also shown applicability even when dealing with relatively small sample sizes [52]. In our analysis, session number was designated as a fixed effect, while the participant ID was incorporated as a random effect, accounting for individual variability. We conducted an analysis of the session effect by evaluating the impact of each time point. Firstly, we performed single term deletions to identify any substantial differences among the different sessions. If we found statistical significance, we proceeded with post-hoc analyses utilizing Tukey’s test. Our specific focus was on comparing the baseline session with the remaining sessions to determine if there was any change in performance. Furthermore, to ensure the validity of our linear mixed-effect models, we conducted residual analysis [53] to confirm that the assumptions of the model were not violated, including testing normality, and homoscedasticity of the residuals using Q-Q plot and the Scale-Location plot, respectively. To further explore the relationships between different variables, we calculated Spearman's correlation coefficients (rho). Specifically, we examined the correlation between SUS scores and the baseline characteristics and training performances of the participants. Furthermore, we investigated the correlation between baseline Fugl-Meyer Assessment of Upper Extremity (FMA-UE/FMA-Wrist) scores and the assessment score as well as between FMA-UE/ FMA-Wrist and the changes in LoD during the dynamic tasks. For all statistics, a significance threshold of $\alpha = 0.05$ was applied.

**Results**

**Participants**

Seven participants completed all ten training sessions and related questionnaires. Demographic data and baseline functional assessments of the upper limb are shown in Table 1.

**Table 1. Participant demographics and baseline functional assessments**
<table>
<thead>
<tr>
<th>ID</th>
<th>Age</th>
<th>Sex</th>
<th>Days post-stroke</th>
<th>Affected hand</th>
<th>Stroke type</th>
<th>Stroke location</th>
<th>FMA-Wrist (max = 7)</th>
<th>FMA-UE (max = 66)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>65</td>
<td>M</td>
<td>39</td>
<td>L</td>
<td>I</td>
<td>Subcortical</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>P2</td>
<td>52</td>
<td>M</td>
<td>145</td>
<td>R</td>
<td>H</td>
<td>Subcortical</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>P3</td>
<td>52</td>
<td>M</td>
<td>46</td>
<td>R</td>
<td>I</td>
<td>Subcortical</td>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>P4</td>
<td>68</td>
<td>M</td>
<td>37</td>
<td>R</td>
<td>I</td>
<td>Subcortical</td>
<td>7</td>
<td>33</td>
</tr>
<tr>
<td>P5</td>
<td>52</td>
<td>M</td>
<td>42</td>
<td>L</td>
<td>H</td>
<td>Subcortical</td>
<td>7</td>
<td>35</td>
</tr>
<tr>
<td>P6</td>
<td>52</td>
<td>M</td>
<td>31</td>
<td>R</td>
<td>I</td>
<td>Subcortical</td>
<td>7</td>
<td>37</td>
</tr>
<tr>
<td>P7</td>
<td>35</td>
<td>F</td>
<td>72</td>
<td>L</td>
<td>I</td>
<td>Subcortical</td>
<td>7</td>
<td>53</td>
</tr>
<tr>
<td>Median</td>
<td>52.0</td>
<td>1F</td>
<td>42.0</td>
<td>3L</td>
<td>2H</td>
<td>All subcortical</td>
<td>7.0</td>
<td>33.0</td>
</tr>
<tr>
<td>[Q1 - Q3]</td>
<td>[52.0 - 58.5]</td>
<td>[38.0 - 59.0]</td>
<td></td>
<td></td>
<td></td>
<td>[20.5 - 36.0]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

F = female; H = hemorrhagic; I = ischemic; L = left; M = male; R = right.

**Usability analysis**

**System Usability Scale (SUS)**

Participants generally offered favorable evaluations for the MyoGuide mobile training platform. The median SUS score in subacute stroke participants was “good” (82.5), as shown in Table 2. Among these participants, one individual assessed the platform as “excellent” (90), while six participants assessed it as “good” (72.5-85), and another participant as “OK” (70). Based on Q1, Q3 and Q9 from SUS, participants generally conveyed their inclination to use the MyoGuide frequently and confidence in their ability to use the system. However, participants still expressed a desire for the availability of technical support during use in Q4. No significant correlations were found between the SUS score and age (Spearman's rho = 0.012, p = 0.798), SUS score and FMA-UE score (Spearman's rho = -0.070, p = 0.878), or SUS score and FMA\textsubscript{wrist} score (Spearman's rho = -0.05, p = 0.910). These results suggest that the perceived usability of the system was not influenced by age or baseline motor function.

**Table 2. System Usability Scale for the MyoGuide Mobile Training Platform on Sub-acute Stroke Survivors**
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1: I think that I would like to use this system frequently.</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>Q2: I found the system unnecessarily complex.</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Q3: I thought the system was easy to use.</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Q4: I think that I would need the support of a technical person to be able to use this system.</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4.5</td>
</tr>
<tr>
<td>Q5: I found the various functions in this system were well integrated.</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Q6: I thought there was too much inconsistency in this system.</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Q7: I would imagine that most people would learn to use this system very quickly.</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Q8: I found the system very cumbersome to use.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Q9: I felt very confident using the system.</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>Q10: I needed to learn a lot of things before I could get going with this system.</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total Score</strong></td>
<td>90</td>
<td>70</td>
<td>82.5</td>
<td>72.5</td>
<td>82.5</td>
<td>85</td>
<td>80</td>
<td>82.5</td>
</tr>
</tbody>
</table>

Likert scale: 1 (strongly disagree), 2 (disagree), 3 (neutral), 4 (agree), 5 (strongly agree). FMA-UE is given in parenthesis after the participant ID.

**MyoGuide Training**

**Level of Difficulty (LoD) in the Dynamic Task**

During the 10-day training program, we observed an increase in LoD for nearly all participants, as shown in Figure 2 (orange symbols). Utilizing a linear mixed-effects model, we found that the fixed factor “session number” reached statistical significance ($p < 0.0001$), indicating a noticeable increase in LoD across sessions. Further analysis using Tukey post-hoc tests revealed a significant difference in LoD starting from the fourth session ($p = 0.003$; mean: 24.80, CI: 4.94 – 44.66) compared to the first session.
and continuing to the final session (p < 0.0001; mean: 45.43, CI: 25.56 – 65.29) as shown in Figure 3. These results indicate a substantial increase in LoD at the group level as training progressed. It is important to note that the increase in LoD was not consistent across all participants, with rates of progression being lowest for the two most impaired patients. This observation was further supported by a significant correlation between the changes in LoD and the baseline FMA-Wrist scores (Spearman's rho = 0.800, p = 0.030) while the correlation between LoD and baseline FMA-UE scores of the participants did not reach significance (Spearman's rho = 0.643, p = 0.120). This observation underscores the notion that individuals with varying degrees of impairment in the target region exhibited distinct progression in LoD. Furthermore, our analysis revealed no significant correlation between the change in LoD and SUS scores (Spearman's rho = -0.020, p = 0.969). This indicates that better progression in LoD did not necessarily translate to higher usability scores.

**Assessment Score in the Stability Assessment**

Over the course of the ten training days, participants exhibited varying trends in their assessment scores. While there was an overall positive trend towards higher scores in most participants, the scores also did not consistently increase for all individuals, as shown by the gray markers in Figure 2. However, our linear mixed-effect model revealed a significant impact of the fixed factor “session number” on the assessment scores (p = 0.020) as shown in Figure 3. Subsequent post-hoc tests revealed a significant difference between the first session and last sessions, with the score in the final session being significantly higher (p = 0.010, mean = 229.43, CI = [25.74 – 433.11]).

Individually, we observed a positive correlation (Spearman's rho = 0.857, p = 0.014) between participants' baseline FMA-UE scores and FMA-Wrist (Spearman's rho = 0.800, p = 0.030) and their average assessment scores, confirming that individuals with less upper-limb impairment generally achieved better performance in the stability assessment task. No significant correlation was found between the mean assessment score and SUS score (Spearman's rho = 0.160, p = 0.798), indicating that better performance in the stability assessment did not necessarily result in higher usability scores.

**Therapist’s Observation and Feedback**

During the training sessions, the two participants with the lowest FMA-UE scores (P1 and P2) required the most support. These participants needed assistance with forearm support and movement guidance. Initially they had to discontinue the training after the first half of the intervention in each session due to fatigue. However, in the last two sessions, they were able to complete almost all training blocks, showing progress in their ability to perform the training. For all participants, the therapist provided verbal information and encouragement, demonstrated the movements, and assisted with navigating through the application (e.g., entering participant ID and choosing training side). These two participants (P1 and P2) underwent training in a supine position, and wrist extension was performed without the influence of gravity. The remaining participants underwent training in a sitting position, performing wrist extension against gravity. Throughout the study, no adverse events related to the training were observed, suggesting that the training protocol and the use of the MyoGuide system is safe for subacute stroke patients.
Future Possibility of Training at Home

Furthermore, participants expressed interest in continuing the training at home. However, the survey also revealed challenges related to the use of the Myo armband and software application in an unsupervised setting. Specifically, participants mentioned difficulties in independently donning the Myo armband and operating the tablet. This indicates that using the MyoGuide platform without supervision will require adequate onboarding, initial guidance and potentially some support. Despite the participants' motivation and positive experiences with training, practical aspects of using the technology independently require further development until its effective implementation in a minimally supervised environment.

Table 3. The possibility of training at home with technology.

<table>
<thead>
<tr>
<th>Survey Question</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>I think the training improved my functional recovery.</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>I need others to help with putting on Myo.</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>I would like to continue the training.</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>I need others to help with operating the tablet.</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>I could perform the training independently.</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>5</td>
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</tr>
<tr>
<td>I would like to take the training device home (if it is free of charge).</td>
<td>5</td>
<td>3</td>
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Likert scale: 1 (strongly disagree), 2 (disagree), 3 (neutral), 4 (agree), 5 (strongly agree).

Discussion

The primary objective of this study was to incorporate usability evaluations into the early phases of MyoGuide development, utilizing a therapist-to-patient ratio of 1:1 in a supervised setting. By gathering insights through usability tests from stroke participants and written reports from the therapist, our aim was to uncover potential usability obstacles they might encounter. This approach not only facilitates the iterative enhancement of the training platform but also strengthens its utility as a clinical tool for therapists.

The usability report revealed the successful use of the MyoGuide training platform by all participants, including those with severe upper limb impairment (P1 and P2, with an FMA_{wrist} score of 0). It enabled training in various positions (supine or sitting). Stroke participants assigned favorable SUS scores ranging between good and excellent (70–90). Notably, the mean SUS score obtained in our study (80.4) compared favorably with similar studies exploring the usability of other novel rehabilitation technologies.
For instance, the mean scores were 69.0 for arm and hand devices with a gaming environment [54], 70.1 for wearable soft-robotic gloves for stroke rehabilitation [55], and 71.9 for a robotic assistive device for home rehabilitation [56].

Early post-stroke rehabilitation is hypothesized to play a crucial role in promoting functional recovery and independence in ADLs [12–15]. However, active training is not easy to implement in clinical settings when patients are still severely impaired. Our findings indicate that the MyoGuide training platform shows promise for use in the early phase of stroke rehabilitation, particularly when a patient’s active movement of the wrist may be limited and might still be bedridden. The results showed that most of the patients could begin training with the platform under the guidance of a therapist following a short familiarization session, emphasizing its feasibility and potential advantages in supporting early-stage stroke rehabilitation.

In addition, all participants indicated that they would be willing to continue to train with the device at home. However, most participants expressed a need for assistance in navigating through the application and placing the armband, which posed a potential barrier to using the system in an unsupervised setting. While stroke participants acknowledged the benefits of the training, the practical aspect of using the technology without external support presented a challenge. These findings indicate that home-based rehabilitation systems will require adequate training of the patients and their caregivers, and that a remote support system might be essential.

Our study also examined the progression of two training components that can be easily assessed online: the assessment score in our stability assessment and the LoD in our dynamic task. LoD in our dynamic task increased with training and the post-hoc multiple comparison analysis revealed a significant increase in LoD starting from the 4th session compared to the 1st session. This signifies an overall adaptation to the training program, as participants were able to handle and perform tasks at higher LoDs as they progressed through the sessions. Notably, participants with moderate to mild impairment (FMA-UE: 31–66, based on [57, 58]) exhibited better progress compared to those with severe impairment (FMA-UE: 0–30), likely attributed to factors such as fatigue resulting from the frequent recalibration process. The impact of fatigue was evident as two participants with severe impairment (P1 and P2) could not complete all training blocks. Similarly, regarding the stability assessment, the correlation analysis demonstrated a significant positive correlation between the average assessment score and the baseline standard clinical assessment for the upper limb (FMA-UE & FMA-Wrist). Moreover, the assessment score did significantly improve across sessions with the assessment score in the 10th session being significantly higher than in the 1st session, indicating that participants made progress in their stability skills throughout the training sessions.

To address the challenge of fatigue, it is crucial to consider the individual abilities and limitations of patients with severe impairment during the calibration process. Additionally, considering that the placement of the armband remained unchanged throughout a session, the need for calibration before every task may not have been necessary. Future adjustments could involve skipping the calibration step if
a participant does not experience significant fatigue from the previous training task. This would optimize the training process by minimizing unnecessary fatigue and providing a more efficient and personalized experience for patients with severe impairment. Additionally, implementing a more tailored approach to LoD, stratified based on the participants impairment level, could enhance the training experience. Participants with better function might begin with more challenging tasks, while those with higher impairment might require adjusted parameters to ensure meaningful participation, such as fewer training blocks, longer rest durations, and shorter task durations.

Through involving end-users early in the development, we gathered user feedback to refine the platform's design, ensuring its applicability in clinical settings. This iterative process pinpointed two key usability challenges – independent armband uses and application navigation – essential for enhancing the platform's usability and effectiveness beyond supervised therapy. While these aspects may not significantly impact the feasibility of using the platform in supervised therapy sessions, they could potentially hinder its adoption in unsupervised settings, such as at home. Therefore, addressing these issues is crucial to enhance the usability and user experience of the platform, promoting its effectiveness and acceptability outside of supervised therapy sessions. Moreover, this study concentrated on the feasibility and usability of the MyoGuide platform in a supervised setting, rather than measuring clinical effectiveness, which remains a focus of future research.

Conclusions

This study introduces the MyoGuide training platform and demonstrates usability in a clinical setting for stroke rehabilitation, with the assistance of a therapist. The findings support the potential of MyoGuide for wrist extension training in patients across a wide range of impairment levels. However, certain usability challenges, such as donning/doffing the armband and navigating the application, need to be addressed to enhance the user experience. Additionally, further improvements are needed in terms of stratification strategies, such as adjusting the starting difficulty based on the level of impairment or providing customizable training programs before the tool can be tested during (i) the acute stage in hospitals or (ii) continued training in minimally supervised settings, e.g., community centers or at the patient’s home.

Abbreviations

FMA-UE
Fugl-Meyer Assessment for Upper Extremity
SUS
System Usability Scale
ADL
Activities of Daily Living
sEMG
Surface Electromyography
LoD
Level of Difficulty

Declarations

Ethics approval and consent to participate

All the participants were duly informed about the study and all of them provided voluntary, written informed consent in accordance with the Declaration of Helsinki. This study was approved by the Ethics Commission at the ETH Zurich and the ethical committee at the Shengjing Hospital of China Medical University.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article and its supplementary information files.

Competing interests

The authors declare that they have no competing interests

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Authors’ contributions

HPL analyzed, interpreted the data, prepared figures/tables, and wrote the manuscript. XY assisted in ethics preparation, participant screening, and data collection. XZ conceptualized the study, applied, and amended the ethics, trained research staff, collected data and assisted in drafting the manuscript. DW conceptualized the study, developed, and maintained the software, and assisted in data management and drafting the manuscript. LZao assisted in data management and ethics amendment. WL assisted in data collection. HJC analyzed data and assisted in drafting the manuscript. LZhang conceptualized the study, applied ethics, and provided research resources. NW conceptualized the study, applied ethics, provided research resources, and oversaw the data analyses. All authors read and approved the final manuscript. All authors reviewed the manuscript.
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References


**Figures**
a. Introduction to the training platform

Figure 1

The study design and MyoGuide application. (a) Introduction phase: a therapist demonstrates the training program and EMG calibration provides reference values for controlling the yellow cursor in the stability assessment and the height and speed of the panda avatar in the dynamic task. (b) Intervention phase: participants underwent 10 days of training, consisting of EMG calibrations, stability assessments, and dynamic tasks. (c) Post-intervention evaluation: the system usability scale and a survey on the possibility of training at home were administered to the patient. The therapist's observations and feedback on training details were documented as well.
Figure 2

The progression of training parameters. The progression of both LoD in orange and assessment score in gray across the 10 training sessions.

Figure 3

Comparison of sessions using single term deletion and Post-Hoc Tukey Test. Single term deletion shows significant differences from baseline session starting from the fourth session in LoD (a). As for Assessment Score (b), the presence of significant differences is only notable when comparing the final session with the baseline. Confidence intervals obtained through the Post-Hoc Tukey Test show the estimated differences between the baseline session and other sessions in LoD (c) and Assessment Score (d). The lower and upper bounds of the confidence intervals are presented below each corresponding line. Note that we treated subject IDs as random factors (1|ID), while session numbers were treated as fixed effects.
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- MyoGuidedataset.xlsx