Feasibility, usability and effectiveness of a robot-assisted finger proprioception therapy

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Research Article

Keywords: robot-assisted therapy, neurorehabilitation, stroke, recovery, proprioception, hand function

Posted Date: February 7th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-3916719/v1

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Additional Declarations: No competing interests reported.
Feasibility, usability and effectiveness of a robot-assisted finger proprioception therapy

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Abstract

Background: Neurological injuries, such as stroke, often lead to motor and somatosensory impairments of the hand. Deficits in somatosensation, especially proprioception, result in difficulties performing activities of daily living involving fine motor tasks. As those impairments are challenging to accurately evaluate and monitor, therapies rarely focus on proprioception specifically, even though it has been shown that such training could promote functional benefits. In this work we propose and preliminarily evaluate the feasibility, usability and effectiveness of a robot-assisted therapy focused on finger proprioception.

Methods: We designed and implemented on an existing robotic platform (ETH MIKE) five therapeutic exercises, focusing on finger somatosensation, two targeting passive and three active position sense. The difficulty level of the therapy exercises was automatically adapted to each patient’s proprioceptive impairment, assessed using the same platform (i.e., assessment-driven therapy). Nine subacute stroke participants completed the robotic therapy for at least two weeks, 30 minutes per day, five-times a week. Data was compared to a control group based on a previously collected dataset where subacute stroke participants received usual care and the same assessments.

Results: We found that the proposed exercises were feasible for stroke participants, as everyone managed to progress in difficulty levels. Moreover, the exercise performance averaged between 59% and 70% of maximum possible performance for the different exercises, indicating adequacy of the difficulty adaptation algorithm and a balance between motivation and challenge. Further, usability was rated as acceptable, as NASA Task Load Index (raw TLX), which provides an overall workload score, was mostly below 50%, except for mental demand. There was a significant improvement in proprioceptive error and in the Box and Block Test score from study inclusion to discharge for the intervention group, which was not the case for the control group.

Conclusions: This work demonstrated the first insights into feasibility, usability and effectiveness of a novel robot-assisted therapeutic approach. These encouraging results pave the way for further development and validation of therapy approaches focusing on somatosensory function.

Keywords: robot-assisted therapy; neurorehabilitation; stroke; recovery; proprioception; hand function
Background

Neurological injuries, such as stroke, can lead to hand somatosensory impairments (prevalence up to 67%), which result in difficulties to perform activities of daily living (ADL) [1–5]. Proprioceptive deficits can be especially disturbing, as the ability to sense the position and movement of the limbs is essential to perform ADLs, in particular fine movements, such as grasping small objects [3, 6]. Proprioceptive impairments are unfortunately only rarely targeted by therapeutic interventions, despite several studies reporting their link to poor functional recovery and higher ADL limitations after stroke [7, 8].

One of the reasons why therapeutic interventions targeting proprioception are rarely used in clinical practice is that these deficits are poorly diagnosed and thus often remain undetected. Somatosensory impairments of the upper limb are generally more challenging to assess, as they are not as clearly recognizable as motor impairments (due to e.g., visible paresis), and, especially in the case of proprioceptive impairments, may even be initially misclassified as originating from problems with motor execution or sensorimotor integration [9]. Further, currently existing clinical assessments, such as the Up-Down Test as part of the Nottingham Sensory Assessment, are subjective, lack sensitivity and are prone to ceiling/floor effects [10]. The lack of sensitive and reliable outcome measures also makes it difficult to evaluate the effectiveness of new interventions [8, 11]. Available therapies targeting proprioception of the upper limb consist of passive and active movement training, where vision is typically constrained so that participants rely on proprioceptive feedback while executing a task involving the hand [12, 13]. Other interventions include somatosensory stimulation (e.g., vibration) or somatosensory discrimination training (e.g., discrimination between different shapes or textures) [13, 14, 14–16]. However, these therapies lack standardization and more studies are needed to prove their ef-
fectiveness using more sensitive outcome measures, hence proprioceptive therapies are currently often deprioritized in clinical practice [8].

Robotic rehabilitation platforms are a promising way to provide more accurate assessments, as well as to train proprioception [17–21]. Such technologies can apply accurate displacements to the limbs and sensitively measure participant’s response [22]. They also provide potential benefits of increased therapy intensity, movement assistance, and patient engagement through gamification of exercises [23–25]. Moreover, technology-aided rehabilitation can allow to choose and adapt the difficulty level of the exercises in a standardized way, based on the outcome of objective assessments performed using the same platform (assessment-driven therapy) [18, 26]. Robotic proprioception therapies reported in clinical studies entail position discrimination exercises [18], replacement of visual feedback by haptic feedback to guide the motion [17] or robot-assisted tracking of a target by the hand and wrist with vision occluded [19, 20]. However, given the challenges of existing clinical proprioception assessments, not many of these approaches follow an assessment-driven therapy principle, thereby not fully exploiting the potential of such technologies to personalize therapy parameters to the current state of the patient [20]. Further, newly proposed robotic solutions often have limited usability, given, among other things, the complexity of the technology [27]. Lastly, currently most robotic platforms focus on proximal joints of the upper limb or gross hand movements, while training finger proprioception could provide additional benefits in manual dexterity, and thus improve performance in many activities of daily living involving the hand [28, 29]. Thus, there is a need for novel robot-assisted therapy approaches focused on distal joints to aid neurological patients in proprioceptive recovery. In order to ensure that such solutions are usable and clinically accepted, relevant stakeholders need to be involved in the design process, especially patients, as higher satisfac-
tion with a robotic therapy experience would likely lead to higher adherence and motivation when performing the exercises [30].

In this work we propose a novel robot-assisted, assessment-driven therapy composed of five exercises focused on finger proprioception. We then evaluate its feasibility, usability and effectiveness in a pilot study with stroke patients over at least 2-weeks intervention and compare the results to a control group that received conventional therapy (recorded as part of a previous study [31]). We consider feasibility in terms of the ability to perform the exercises and increase performance, while usability is defined in terms of perceived mental demand, performance and enjoyment of the therapy. Our objective is to gain insights from this preliminary evaluation for future improvements of the proposed therapy approach. The therapy exercises were implemented on the robotic platform ETH MIKE (Motor Impairment and Kinaesthetic Evaluation) focusing on the training of the index finger metacarpophalangeal (MCP) joint [32]. This platform has so far been used and validated for assessment purposes in stroke patients, persons with multiple sclerosis and children with unilateral cerebral palsy [33–35]. We hypothesize that the proposed proprioception exercises are feasible and that they show effectiveness for stroke patients, given that the therapy design has been inspired by previous work, as well as by clinical principles of sensory re-education [16, 18, 36]. High usability is expected due to an intuitive graphical user interface and personalized difficulty levels. This work aspires to contribute to the field of neurorehabilitation with a novel robot-assisted assessment-driven therapy of finger proprioception, which might ultimately aid in the recovery of hand dexterity in patients with sensorimotor disabilities.

**Methods**

**Participants**

Study participants were recruited as soon as they entered the rehabilitation centre Kliniken Schmieder Allensbach, Germany, where they received inpatient multidiiscipl
plinary treatment (usual care). Inclusion criteria were: age >18 years, diagnosis of stroke (ischemic or haemorrhagic), less than 3 months post-stroke, and the ability to passively move the participant’s MCP joint of the index finger by at least 20°. Exclusion criteria were: inability to understand instructions, pain when moving the MCP joint, diagnosis of visuospatial neglect (Bells Test [37]) or aphasia. All participants gave written informed consent before participating in the study. The study was approved by the Ethics Commission of Baden-Württemberg F-2016-126 and registered as a clinical trial[1].

Apparatus

The ETH MIKE is a one degree-of-freedom end-effector robot, which can provide well-controlled stimuli to the index finger and sensitively measure its kinematic and kinetic responses [32, 33]. The end-effector of the robot has the center of rotation aligned with the MCP joint of the index finger (Figure 1). Participants are seated in front of the device and the hand is placed grasping an easily exchangeable, 3D printed handle, while the index finger is stretched and attached to the end-effector via Velcro straps. A tablet computer (Microsoft Surface Pro 6, refresh rate 60 Hz) with a touch screen is placed directly above the hand, displaying a Graphical User Interface (GUI), which allows the experimenter to start/stop exercises and for the participants to interact with the screen to perform the exercises. It also occludes vision of the hand so that visual feedback does not interfere with proprioception testing and training. For a more detailed description of the apparatus, please refer to [32, 33].

Baseline robot-assisted assessments

The ETH MIKE platform was previously primarily used for assessment purposes, and the full assessment battery consisting of five tasks, together with their clinimetric properties, has been detailed in previous work [33]. For the purpose of the

assessment-driven therapy proposed in this work, a selection of two assessments was used.

**Gauge Position Matching**: in this assessment of proprioception, the participant’s index finger is passively moved by the robot from an initial position (neutral finger position) to a randomly selected position in flexion (between 10-30°, with every 2° being tested once). The participant is then asked to indicate the perceived finger position on the screen above, while vision of the hand is restricted. The outcome measure is the Absolute Error (AE) between the actual and the perceived position (°) [33, 38].

**Active Range of Motion**: this assessment is performed to ensure that the active movements required by participants during the exercises are not outside of their active range of motion. In this assessment participants are asked to move their index finger to the maximum reachable position in flexion and then in extension. The outcome measure is the total active range of motion (AROM, in °) [33].

**Robot-assisted proprioception therapy exercises**

The five proprioception therapy exercises and difficulty adaptation algorithms are inspired from our previous work and experience with another hand rehabilitation robot [18, 36]. Two of the proposed exercises (Passive Matching and Trajectory Perception) do not require active movement, which makes them suitable for individuals without remaining motor function (passive exercises). The other three exercises require active movement and are referred to as active exercises (Active Matching, Teach & Reproduce, Haptic Bump). The GUI of all exercises has a simple design, similar to the design of the GUI of the assessments, consisting of a gauge and needles of different colours with unique meaning, such as the target position, and the possibility to guide the task execution by providing red/green feedback based on performance (example of two exercises in Figure 2). Indeed, the key difference between assessments and therapy exercises lies in the fact that therapy exercises provide
visual feedback on the performance after every trial (indicating that the response was correct/wrong and showing the correct answer), which promotes learning and continuous improvement. The five exercises are described below.

**Passive Matching**: this exercise targets the ability to perceive the position of one’s finger in the plane. While vision of the hand is occluded by the placement of the tablet, the participant’s finger is passively moved by the robot to one of \( n \) equally-spaced positions, where \( n \) depends on the difficulty level (i.e., 2 to 6). Each possible \( n \) position is visually represented by a needle of a specific colour. Participants need to indicate the perceived position by clicking on the button with the corresponding colour (Figure 2A). Directly after selecting the answer, visual feedback is provided (correct answer is highlighted in green, the wrong choice in red).

**Trajectory Perception**: this exercise targets perception of movement (kinaesthesia) [6]. The GUI is the same as for Passive Matching (Figure 2A), but the procedure of the exercise is different. Here, the participant’s finger is passively moved by the robot to one of \( n \) equally-spaced positions (\( n \) ranges from 2 to 6 depending on the exercise difficulty level) and back to start. Participants need to indicate the perceived movement amplitude by clicking on the button with the colour corresponding to where the finger was moved to. Directly after selecting an answer, visual feedback of the correct answer is provided (Figure 2C) to facilitate learning.

**Active Matching**: this exercise focuses on the ability to perceive one’s finger position and move the finger to a desired location. In this exercise the participant’s finger is moved by the robot to the starting position (grey needle, Figure 2B). Then, participants need to move their finger as accurately as possible to the position they feel corresponds to a green target, while vision of the hand is occluded. There is no time constraint and once they feel they have moved their finger to the correct position, participants need to press a green confirmation button on the tablet screen.
using the other hand. At this point visual feedback is shown indicating the actual finger position (in blue) and whether it is within a green shaded area of allowable error. This shaded area is defined as a function of the participant’s Absolute Error as measured by the Gauge Position Matching assessment and automatically decreased by a pre-defined factor as participants progress through different difficulty levels. The GUI of this exercise is shown in Figure 2B.

**Teach & Reproduce:** this exercise focuses on movement perception and its reproduction. The finger is first passively moved by the robot to a position in flexion and back to the start (Teach phase). The participant needs to then reproduce this movement by actively moving their finger to the perceived position to which the finger was previously moved to, and press "Validate" (Reproduce phase). After that, visual feedback of the target and actual finger position are displayed, together with the margin of error (green shaded area). As in the Active Matching exercise, the margin of error is personalized to the initial proprioception assessment and automatically adapted as participants progress through the difficulty levels. The GUI is kept the same as for the Active Matching exercise, except that during the Teach phase no needle is displayed to reduce all visual distractions while participants need to focus on the movement perception.

**Haptic Bump:** this exercise focuses on haptic perception. Participants need to move their finger within the device’s workspace to find a spot of increased resistance, which could be perceived as going over a "bump". Once found, participants need to keep their finger within this "bump" and indicate on the tablet screen, located directly above the hand, the perceived location of their finger, by dragging the gauge needle to that location. Once ready, the "Validate" button needs to be pressed and visual feedback is provided, showing the actual location of the "bump", current position of the participant’s finger and the allowable margin of error. Similarly to the other active exercises, the allowable margin of error is personalized to each
patient’s impairment profile and adapted as they progress through difficulty levels.

The GUI is kept the same as for the Active Matching and Teach & Reproduce exercises.

In this study, for each exercise, one exercise run consisted of 15 trials. An exercise run was defined as a sequence of actions from when the finger was moved from the starting position (passively by the robot or actively by the participant depending on the exercise type) until the participant selected an answer (passive tasks) or selected the ”Validate” button (active tasks). Before each exercise run, there were three practice trials during which visual feedback of the current finger position (blue needle) was shown for the whole duration of the trial, to facilitate the familiarization with the exercises, similarly to what has been done previously [16, 18].

**Assessment-driven therapy concept**

The principles of the assessment-driven therapy used in this study have already been described in our previous work [39]. Briefly, the starting difficulty of the proposed exercises is personalized to each patient based on their score on the Gauge Position Matching assessment and the Active Range of Motion Assessment (for active exercises only), to ensure they are challenged within their individual capabilities. The difficulty level is then adapted after each exercise run by automatically increasing, decreasing or maintaining the difficulty level.

Specifically for the case of the Passive Matching and Trajectory Perception exercises, the distance between needles displaying possible finger positions is adapted. The smaller the proprioceptive error in the baseline assessment, the closer the needles, which makes it more difficult to distinguish between them. For the active exercises (Active Matching, Teach & Reproduce and Haptic Bump), the proprioception assessment score is used to adapt the allowed margin of error, that is by how much the actual finger position is allowed to miss the target (Figure 2). Moreover, for these exercises, the range within which the target positions can occur is adjusted.
according to the Active Range of Motion of each subject. The full equation defining
the adapted exercise parameter is:

\[ \Delta = AE \times DF(L) \times SF \]

where \( \Delta \) - distance between needles / margin of error, \( AE \) - Absolute Error, \( DF(L) \) - difficulty factor based on the difficulty level, \( SF \) - scaling factor (preventing ceiling/floor effects).

Further, the difficulty level for each exercise can be increased or decreased based on the percentage of successful trials in a completed exercise run. The therapy always starts at level 1 at the beginning of the study. In the adaptation mechanism, an optimum challenge point was chosen at 70\% success rate, which has been suggested to guarantee a good balance between motivation and effort \([18, 40, 41]\). The automatic difficulty level (\( L \)) adaptation routine was defined based on performance (\( P \)), inspired from \([41]\):

\[
\begin{align*}
L + 2 & \quad \text{if } P = 100\% \\
L + 1 & \quad \text{if } P \in [70, 100]\% \\
L & \quad \text{if } P \in [40, 70]\% \\
L - 1 & \quad \text{if } P \in [10, 40]\% \\
L - 2 & \quad \text{if } P \in [0, 10]\%
\end{align*}
\]

For each level, specific game parameters (difficulty factors DF) are defined. The higher the level, the smaller the DF (for all exercises the DF ranges from 1.5 to 0.6, decreasing by 0.1 for each level increase). Moreover, for the passive exercises, the number of displayed options to choose from increases for higher levels. For all exercises, 12 difficulty levels were defined. To avoid a ceiling effect in case of reaching
level 12, and to avoid a floor effect in level 1, an additional scaling factor (SF) is introduced. It is equal to 1 by default. However, if a participant performs below 40% while being at level 1, SF will increase by 0.1 for the next run. If a participant is already at level 12 but performs above 70%, the SF will decrease by 0.1.

Study protocol

The intervention took place over three weeks, with a session with the robot five times a week, 30 minutes per day (2x robotic assessment sessions at baseline and at the end of the study, and 13x robotic therapy sessions in between). Moreover, every 4 days a usability evaluation was performed. These therapy and assessments sessions were provided in addition to the conventional therapy received by the subacute stroke patients. The protocol is summarized in Figure 3.

The clinical assessments included in the study protocol were the Box and Block Test (BBT) \cite{42} to evaluate manual dexterity and the Montreal Cognitive Assessment (MoCA) \cite{43} to assess cognitive impairments. No clinical assessments of hand proprioception were included in the study protocol due to their limitations \cite{10,33}. Robotic assessments consisted of the two tasks (Gauge Position Matching and Active Range of Motion), although the latter was only used to personalize the exercises, not as a outcome measure of the study.

The robotic therapy performed on each specific day consisted of a selection of three out of the five exercises. In case of patients with AROM below 10° (with hand paralysis), only passive exercises were selected. For the group that was able to move their finger actively, the predefined choice of three exercises was the same for all patients, and included one passive and two active exercises. Among the selection of three exercises, two runs, each consisting of 15 trials, were performed for each exercise. Assessments and exercises were performed on the most affected side (paretic side). The exact selection of exercises per day is shown in Figure 3.
(top row includes active exercises, second row does not, as this is the selection for patients with hand paralysis).

The usability evaluation by patients consisted of the NASA TLX (outcome measure - raw TLX) to quantify perceived task workload [44]. All exercises were rated together as a combined therapy experience when filling in the NASA TLX. Patients also rated each performed exercise in terms of preference, as well as perceived challenge, on a scale from 1 to 5.

Effectiveness was evaluated by comparing the results of the robotic therapy intervention to a control group, which received conventional therapy only. The control group was built based on the dataset from a longitudinal observational study performed previously by our group [31] (separately registered as a clinical trial [2]). The previous study had exactly the same inclusion criteria, and the time interval between the two robotic assessments was comparable. The control group was built by scanning the 45 participants of the longitudinal study to match each individual of the interventional study in terms of baseline proprioception (AE) and baseline BBT score. The scanning was done blinded to the discharge scores from the longitudinal dataset.

Statistical analysis

Descriptive statistics are reported as mean and standard deviation (mean ± SD). Feasibility of the proposed robotic therapy was quantified in terms of the number of participant drop-outs (patients that did not complete both baseline and discharge assessments), and the occurrences of adverse events. Moreover, the ability of participants to increase in difficulty levels and to reach the desired performance of 70% on the robotic therapy exercises was also evaluated as part of the feasibility measure. The individual performance and increase in difficulty levels were correlated with

the change in the assessments outcome measures from baseline to discharge using Spearman correlation.

The effect of participation in the robotic therapy sessions on the perceived task load was evaluated by comparing the four usability evaluations performed over the study duration. We set a threshold of desired task workload (raw TLX) of below 50% for all sub-parts of the NASA TLX questionnaire, inspired by [41]. Further, all exercises were compared in terms of subjective rating of perceived challenge and personal preference. For this analysis we used the data from the latest study day at which both the exercise and the usability evaluation were performed. For this analysis, only patients that performed all passive and active exercises were considered (i.e., subjects able to actively move more than 10°, case 1 in Figure 3).

To evaluate effectiveness, firstly the control and intervention groups were compared in terms of time since stroke at baseline and discharge, as well as BBT and AE at baseline, using an independent samples t-test. In case of non-normal data distribution (evaluated using Shapiro-Wilk test), the Wilcoxon rank sum test was used instead. The difference between baseline and discharge assessment scores within each group was then compared [20]. When the difference between the pairs was normally distributed, a paired-samples t-test was used. In case of non-normal distribution, the Wilcoxon signed-rank test was used. The main outcome measures of interest for this comparison were AE and BBT.

Results

Fourteen stroke participants were recruited to take part in the robotic intervention, 9 of those completed the baseline and discharge assessments and their data was used for the analysis. Out of the 9 participants that underwent the intervention and performed the two assessments, 2 participants had insufficient motor function to perform active exercises (hand paralysis), and thus performed only passive exercises throughout the protocol (case 2, Table 3). The control group was composed to also
consist of 9 participants with matching baseline characteristics. Detailed participant information is provided in Table 3.

Feasibility

The drop-out rate of the study was 36% (5 drop-outs in 14 patients recruited). The reasons for drop-outs were: illness (Covid-19), transfer to another hospital, other accompanying medical conditions that led to discontinuing the study (e.g., hand swelling unrelated to the intervention), fatigue by the frequency of appointments and hence unwillingness to continue (two participants). Further, among the nine participants that completed the pre- and post assessment, two performed the therapy exercises for two instead of three weeks due to early discharge, but were nevertheless still included in the analysis. The average number of therapy days among the nine participants was 11.78 ± 1.92. The average therapy session duration was 26min ± 3min and the average total therapy time 5h7min ± 48min. This corresponded to a total of 1060 ± 146 exercise repetitions over the therapy duration and an average therapy intensity of 3.45 ± 0.13 repetitions per minute. There were no adverse events reported during the study. All participants managed to increase in difficulty levels at least once over multiple exercise runs in all exercises they performed and the average difficulty level across all participants continuously increased over exercise runs (Figure 4).

The number of times participants increased in difficulty levels varied across the exercises (Figure 4). The average level reached by the 10th exercise run ranged from 4 to 6 for the different exercises. The exercise performance (% correct trials per exercise run), averaged across all runs and participants, was the lowest for the Haptic Bump exercise (59.83% ± 7.41%) and the highest for the Trajectory Perception Exercise (70.02% ± 8.69%), as detailed in Table 1. Overall, the average performance oscillated around the desired 70% over exercise runs, although it tended to decrease over time with increasing difficulty level (Figure 4). This was especially the case
for the passive exercises, which were repeated up to 40 times by the participants with hand paralysis, for whom the difficulty level stabilized towards the end of the intervention (Figure 4f).

Moreover, the average performance varied across participants, ranging from 55.11% to 75.99% (averaged across all runs of all exercises), as shown in Figure 5. Higher average exercise performance was correlated with larger change in the proprioception assessment score ($\rho=0.73$, $p=0.03$). The same trend was observed for average maximum level reached ($\rho=0.60$, $p=0.10$), although the correlation was not significant, influenced by an apparent outlier (#13). This participant was the only one with large decrease in performance in the Gauge Position Matching task between baseline and discharge assessments (Table 3). The correlation between the performance and change in BBT was not significant, however a trend of larger gains for those that on average performed better in the exercises was still observed when removing participants #8 and #13 with hand paralysis (Figure 5).

Usability

Overall, the task load index was acceptable (below 50%) for all aspects of NASA TLX, except for mental demand (average 52.50% ± 18.62 across four evaluation times). Nevertheless, mental demand decreased over therapy duration to 46.25% ± 22.64%. The aspect that received the lowest raw TLX score was temporal demand, although it did increase over time from 7.50% ± 17.53% to 16.25% ± 19.96%. The raw TLX score for frustration and perceived performance also increased over time, as detailed in Figure 6. The perceived performance on average tended to be lower then the actual performance, although both did decrease towards the end of the study (actual performance: decrease from 61.01% ± 24.83% to 54.58% ± 14.76 from the first to the last therapy session, perceived: 60.00% ± 15.00% to 36.25% ± 20.66%). Lastly, when comparing the 5 exercises, Haptic Bump was found the most challenging, but it was also the most preferred exercise. In general, active exercises
were found more challenging than passive. In terms of preference, after the Haptic Bump exercise, the two passive exercises were preferred, which were also the two exercises in which patients reached the highest performance (Table 1).

Effectiveness

The intervention and control group were comparable at baseline in terms of demographics. There was no significant difference in AE (9.9° ± 4.2° intervention, 10.3° ± 4.3° control group, p=0.80), BBT (24.1 ± 23.2 blocks/min, 22.7 ± 23.7 blocks/min, p=0.98), MoCA (21.8 ± 3.5, 21.2 ± 5.4, p=0.95) or time since stroke (36.1 ± 16.9 days, 33.0 ± 10.8 days, p=0.65) at baseline between the groups. There was also no significant difference in time since stroke at discharge between these groups (53.1 ± 17.6 days, 46.4 ± 13.7 days, p=0.38).

When comparing the inclusion and discharge assessments, both groups decreased the proprioceptive error AE and improved in BBT, although the intervention group demonstrated larger improvements (Table 2). The difference in BBT between inclusion and discharge was significant for the intervention group, which was not the case for the control group. In the intervention group there was a consistent decrease in AE for all but one participants, who performed worse on the discharge assessment (#13, Table 3). This participant also reported the highest frustration and decreasing interest in the therapy, as this participant was one of the two that performed only passive exercises due to hand paralysis (#8 and #13). When removing this participant from the analysis, the baseline difference between groups remained non-significant. The difference between the two assessment points in AE and BBT for the intervention group was significant in this case, while it remained not significant for the control group (Table 2).

Discussion

This paper presents the design and preliminary evaluation of a novel robot-assisted assessment-driven therapy of finger proprioception for individuals after a stroke.
The main novelty lies in the fact that the proposed therapy targets proprioception of distal joints, while most clinical and robotic therapies focus on gross motor function of proximal joints of the upper limb [12, 14, 17, 18, 20]. Improving distal proprioception could positively affect fine motor control and hence improve performance in ADLs [6, 13, 17]. Moreover, therapy parameters were personalized to each participant’s baseline impairment (assessment-driven therapy), based on validated assessments performed on the same robotic platform. The exercise difficulty then automatically adapted throughout the intervention, ensuring that patients stay motivated and sufficiently challenged. We found that the proposed therapy was feasible to be performed by subacute stroke patients, given an, on average, increase in difficulty level over three weeks of the intervention, confirming the suitability of the adaptation algorithm. The exercises were also shown usable through acceptable task load evaluation results. Finally, we demonstrated promising effectiveness of the proposed therapy.

Feasibility

As a measure of feasibility, there was a trend of increasing difficulty level over exercise runs for all patients, which indicates a general understanding of the exercises, as most subjects were able to complete them correctly. The performance oscillating around the desired 70% window confirms that the difficulty was appropriately adapted to the participant’s capabilities, keeping the balance between motivation and challenge [18, 40, 45]. The measure of performance was found to not only be an exercise-specific parameter, but also convey functionally meaningful information. This is because participants that performed better in the exercises tended to improve more in hand function, which is in line with previous work [18]. Higher performance might indicate a greater mental and physical engagement in the training, translating to functional gains.
Nevertheless, it is also worth noting the relatively high drop-out rate of the study (36%), which presents a challenge for the feasibility of the proposed 3-week intervention. While most of the reasons for drop-outs were actually unrelated to the robotic therapy itself (e.g., illness, change of clinic), fatigue due to the frequency of appointments was a relevant factor. It needs to be noted that the robotic therapy was received in addition to already intense conventional therapy programs. High dose of therapy has been shown to be required to show therapeutic effectiveness, hence reducing frequency of appointments would not be a desirable solution. Instead, in future studies, efforts should rather be made to increase patient engagement through further improvements to the gamification of the therapy exercises or novel ways to incentivize participants to comply with the full study protocol in order to reduce the drop-out rate [46, 47]. For example, the GUI of the exercises could benefit from a more motivating storyline, since immersive game environments have been shown to increase patient’s engagement [48].

When comparing different therapy exercises in terms of feasibility, the average level reached in the active exercises was lower than in the passive exercises, which indicates that the former are more challenging. This was confirmed by subjective reports of patients and could be explained by the fact that the passive exercises have a limited number of choices (e.g., three positions to choose from), while the active exercises require not only to understand one’s finger position in the plane but also use this information when generating movement. Linked to that, the average performance in the active exercises was also lower than for the passive exercises. Patients tended to prefer the exercises in which they reached higher performance, which is aligned with another study showing that when asked, patients felt the most motivated when reaching performance above 75% [49]. Hence, it is worth considering adapting the desired difficulty adaptation threshold to above 75% for future studies. The exception was the Haptic Bump exercise, which participants found challenging
but most preferred, likely due to the unique feature of the robotic therapy - the haptic rendering, that participants found enjoyable. Hence, in the future it would be beneficial to include more exercises involving haptics, which would stimulate not only proprioception, but also haptic and tactile perception.

Usability

Overall, usability was acceptable, based on the task load index. The task load was mostly rated below 50%, except for mental demand (46%-58%), which can be explained by the fact that the exercises required high levels of concentration and increased body awareness as reported by patients, especially given the personalization of exercise difficulty. Indeed, the automatic difficulty adaptation ensured that patients remained challenged, but also led to the fact that patients rated the exercises as rather mentally demanding. It is generally expected for somatosensory training to be more mentally demanding than pure motor exercises. The mental demand, as well as high frequency of exercise sessions, are necessary for a therapy to prove effective, since sensorimotor learning requires mental engagement and high number of repetitions [50, 51]. Moreover, mental demand tended to decrease over time, indicating a beneficial effect of practice. Conversely, perceived performance decreased and frustration increased over time. Likely these two aspects are linked, as patients feel more motivated when receiving positive feedback [49]. Indeed, the actual and perceived performance showed a high degree of correspondence. Both decreased towards the end of the therapy when patients reached high difficulty levels and also, in some cases, their perception thresholds. This was especially the case for participants that already started the therapy with small proprioceptive error and a further increase in difficulty levels led to the difference between displayed options (for passive exercises) or allowable error (for active exercises) being close to the patients’ just noticeable difference of position perception [52]. An example of such case was patient #13, who not only started with small AE (5.96°), but also
had hand paralysis, hence completed more exercise runs of the passive exercises than the other patients (up to 40 runs), reaching a high level of difficulty (up to level 8). Interestingly, while the actual performance in the exercises only decreased from 63% to 57% for this patient, the perceived performance changed from 80% to 50%. The trend of performance underestimation towards the end of the therapy was observed for all participants (on the last therapy session the actual performance was 54.58% ± 14.76% compared to a perceived performance of 36.25% ± 20.66%). This indicates that perhaps the directness of negative feedback in the current exercise implementation might stimulate self-criticism. Decreased perceived performance and increased frustration towards the end of the study, especially prominent for patient #13, might have influenced the results of the discharge assessments, as this patient might have also lost interest in putting effort into the discharge assessment. Future developments will consider including a more diverse range of passive exercises, as well as introducing a non-linear factor to the difficulty level equation to slow down the increase in difficulty when reaching higher levels.

Effectiveness

Next to feasibility and usability, we also demonstrated preliminary results with respect to the effectiveness of the proposed robotic therapy. The effectiveness was quantified in terms of larger improvement from baseline and discharge in proprioception (AE) and manual dexterity (BBT) in the group that received the intervention compared to a control group receiving only usual care. Moreover, the difference between baseline and discharge in AE and BBT was statistically significant for the intervention group only (when removing an outlier). A general trend of improvement occurring in both groups could have been expected due to both groups receiving conventional therapy and a contribution of spontaneous recovery processes in the subacute phase of stroke [53]. Larger gains in AE observed for the intervention group could be explained by the robotic therapy specifically targeting proprioception. This
result is aligned with literature showing that somatosensory training could help improve proprioception, previously demonstrated not only in stroke patients [54], but also in neurologically intact individuals [17]. Other than the actual physiological change facilitated by the training, familiarization with the platform could have also contributed to the improvement in proprioception, especially given the similarity of the therapy GUI to the assessment interface. Nevertheless, we also demonstrated larger functional gains in the group that received the proprioceptive intervention. Even though the therapy was delivered to the index finger only, it might have also benefited the ability to perform a dexterous task involving also other fingers in order to grasp small blocks (Box and Block Test). Indeed, the index finger is relevant for many ADLs (especially involving dexterous hand movements, such as pinching or precision tasks [55]) and the MCP joint is essential for the synergistic motion with other fingers during grasping [56]. Proprioception training, also involving isolated joint movement (e.g. finger or wrist) has already been shown to result in improved performance in untrained motor tasks (e.g., BBT or robotic tracking tasks) [13, 17, 19, 54, 57]. The reason is that proprioception is essential for fine motor control, as it provides feedback on body position, which is needed to generate accurate motor output [9]. We could speculate that modulation of the integration of proprioceptive feedback in the motor cortex through designated training positively contributes to motor learning, thus leading to improvement in a dexterous tasks such as the BBT [58]. Nevertheless, proprioceptive training should be treated as a complement, especially beneficial for fine motor control, rather than replacement of upper-limb motor therapy, as it has been shown that motor therapy is the most effective for motor improvement early after stroke (as measured by the Fugl-Meyer assessment) [59].
Limitations

A limitation of this work is the lack of dose- or intensity-matched control group, as the intervention group in this study received the robotic therapy in addition to usual care. The control group was built from an existing dataset from a previous longitudinal observational study, in which participants received conventional therapy (usual care). This design was chosen as this study was aimed to serve as a preliminary evaluation before proceeding to a larger, randomized, controlled trial. The exact information about the dose of conventional therapy received by both groups was not available, although expected to be similar. Another limitation to consider is linked to the process of selecting subjects for the control group from the existing dataset. This was done solely based on matching baseline AE and BBT scores on a per-subject basis, although one can argue that a different selection could have led to different results. It should also be noted that direct comparability of the control and intervention groups in terms of BBT scores at discharge is limited by the difference in measurement time point. The control group was in fact assessed up to 2 weeks later (at 4 weeks from baseline) than the intervention group using the BBT. This was only the case for the BBT, while for AE the assessment time-points were comparable, which was linked to the longitudinal study protocol [31]. However, the later assessment timepoint should act in the advantage of the control group, since these patients received additional 2 weeks of conventional therapy. Lastly, for a more comprehensive evaluation of the effect of the proposed therapy on proprioception, it would be required to additionally evaluate this function using an alternative assessment method than the Gauge Position Matching task implemented on the same platform as the therapy. This is to avoid any interference with the effect of familiarization with the platform. However, it was challenging to use clinical assessments for this purpose, given limitations of these scales (ceiling/floor effect, subjectivity, ordinal scale [10]). The proposed therapy exercises were thus
designed carefully to avoid too much resemblance with the proprioception assessment task on the ETH MIKE. Finally, small sample size is a limitation of this study. Nevertheless, feasibility and usability were the focus of this study in order to further improve the development of the therapy solution, after which further evaluation of the therapeutic efficacy could be evaluated on a larger sample size.

Conclusions

To conclude, the presented robot-assisted assessment-driven therapy of finger proprioception is feasible, usable and showed promising effectiveness in subacute stroke participants. It was feasible to keep patients engaged and challenged throughout the therapy thanks to the proposed exercises and difficulty adaptation strategies. Such personalized approach is possible thanks to the use of robotics, since a sensitive assessment and tailored therapy of proprioception can now be conducted on the same platform. This work is a first step to create an effective personalized approach to the training of finger proprioception, which could have a positive long term impact on the recovery of manual dexterity in stroke survivors.

Acknowledgements

The authors would like to thank Thomas Hassa, Jana Stürner and other clinicians at Kliniken Schmieder Allensbach for their help in the development of the robot-assisted therapy concept. We also thank Nick Baumann, Kamil Ritz and Chiara Meli for their help in the implementation of the therapy software.

Funding

This work was supported by the Swiss National Science Foundation, project 320030L_170163, by the ETH Zurich Foundation in collaboration with Hocoma AG, by Deutsche Forschungsgemeinschaft (DFG) and by the National Research Foundation, Prime Minister’s Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme.

Abbreviations


Availability of data and materials

The data presented in this manuscript are available upon reasonable request and under consideration of the ethical regulations.
Ethics approval and consent to participate
The study was approved by the Ethics Commission of Baden-Württemberg F-2016-126 and retrospectively registered as a clinical trial nr DRKS00027932.

Competing interests
The authors declare that they have no competing interests.

Consent for publication
Not applicable.

Authors' contributions
Study design: MZM, RR, CMK, RG, JL, OL. Data collection: MZM, CS, AS, LJ. Data analysis: MZM, RR, CMK. Data interpretation: MZM, RR, CMK, RG, JL, OL. Manuscript writing: MZM, RR, OL. All authors read and approved the final manuscript.

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References


27. Celian, C., Swanson, V., Shah, M., Newman, C., Fowler-King, B., Gallik, S., Reilly, K., Reinkensmeyer, D.J.,


Figures and tables
Figure 1: ETH MIKE robot for the assessment and therapy of hand proprioception. The platform focuses on the index finger metacarpophalangeal (MCP) joint. It consists of an end-effector of the robot where the finger is inserted and secured using Velcro straps (right image), as well as a tablet computer placed directly above the hand (left image), which displays the graphical user interface of assessments and therapy exercises. The robot can either move the user’s finger (passive tasks) or be actively moved by the user (active tasks). Interaction force, velocity and position signals are recorded via integrated sensors.

Figure 2: Visualization of the graphical user interface of the two example therapy exercises, one passive (Passive Matching) and one active (Active Matching). (a) The goal of the Passive Matching exercise is to choose, on the tablet screen located directly above the hand, among presented options, the location of one’s finger after it has been passively displaced by the robot. The choice is made by pressing a button on the touch screen corresponding to the color of the perceived position. (b) In the Active Matching exercise participants need to move their finger as accurately as possible from the starting position (grey needle) to the target position (green needle). (c-d) Visual feedback is provided after every trial to facilitate learning. In (c) the pink needle indicates an incorrect answer that was selected by the participant (e.g., orange instead of yellow). A correct answer would be indicated by a needle highlighted in green. In (d) the blue needle indicates the actual finger position, while the green shaded area shows the margin of allowable error.

Figure 3: Summary of the study protocol. It consisted of clinical and robotic assessments at baseline (study inclusion) and post-intervention (study discharge), 13 days of robotic therapy (30 min per day, 5 days a week) and usability evaluation conducted every 4 days. Each robotic therapy session consisted of 3 exercises, 2 runs of each, with 15 trials per run. For patients that could actively move their index finger by more than 10° the protocol consisted of a predefined combination of the battery of 5 exercises. For patients who could not actively move the hand due to severe paresis the robotic therapy protocol consisted of a combination of 2 passive exercises (case 2, second row in the table).
Figure 4: (a-e) Performance in each exercise (% of trials with a correct answer) and difficulty levels at which the exercise runs were conducted (1-12). Performance is shown as mean and standard deviation across all stroke participants per exercise run (each run consisting of 15 exercise trials), only considering runs that were performed by all participants (because two participants performed more runs in Passive Matching and Trajectory Perception, but these runs were not considered in plots a-e). The difficulty levels are shown as the average across all stroke participants (N=7 for exercises involving active hand movement, N=9 for passive exercises). A dashed blue line represents the target performance of 70%. (f) Each dot corresponds to the difficulty level per exercise run, one participant per colour. Participants #8 and #13 were highlighted as they performed only passive exercises, hence more exercise runs were completed by these individuals for the Passive Matching task.

Figure 5: Difficulty level increase (b) and exercise performance (a) correlate with improvement in proprioception. A similar trend was observed between performance and change in BBT, when excluding participants with severe hand paresis (c). The exercise performance per subject is taken as the average across all runs and all exercises. The difficulty level is the maximum level reached throughout therapy averaged across all exercises. Abbreviations - AE: Absolute Error, BBT: Box and Block Test, ∆: difference between discharge and baseline assessment score. Numbers next to the data points correspond to participant number. The dashed line represents a linear fit. The rho reported next to the line is the Spearman correlation coefficient.

Figure 6: Results of the raw NASA TLX indicating the perceived task load as indicated by participants (N=9). The smaller the score, the lower the perceived workload. The evaluation was performed every 4 days over the 3 weeks intervention and considering all exercises together as a whole robotic therapy experience. It is desired for the raw TLX values to be below 50% (red line).
Table 1: Comparison of the 5 exercises among the participants that completed all exercises (N=7). Performance (%) is the actual performance (% of correct trials) obtained by the participants throughout therapy across 10 runs. Preferred [1-5] row corresponds to the subjective rating of the participants of the preference of each exercise, rather from 1 (least preferred) to 5 (most preferred). Challenge [1-5] row corresponds to the subjective rating by participants of how challenging each exercise was, where 1 corresponded to least challenging and 5 to the most challenging. The perceived preference and challenge were obtained from the last therapy session at which the usability evaluation was performed. Abbreviations: PM: Passive Matching, TP: Trajectory Perception, AM: Active Matching, TR: Teach & Reproduce, HB: Haptic Bump.

<table>
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<tr>
<th></th>
<th>PM</th>
<th>TP</th>
<th>AM</th>
<th>TR</th>
<th>HB</th>
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</thead>
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<td><strong>Performance (%)</strong></td>
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<td>70.02 ± 8.69</td>
<td>63.15 ± 8.16</td>
<td>65.93 ± 8.63</td>
<td>59.83 ± 7.41</td>
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<td><strong>Preferred [1-5]</strong></td>
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<td>3.86 ± 0.90</td>
<td>3.17 ± 1.33</td>
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<td><strong>Challenge [1-5]</strong></td>
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<td>3.57 ± 1.40</td>
<td>3.67 ± 1.21</td>
<td>4.11 ± 0.56</td>
<td>4.29 ± 0.95</td>
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Table 2: Comparison of inclusion and discharge assessments within groups.

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<th>Outcome</th>
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<th>Discharge</th>
<th>Delta</th>
<th>p-value</th>
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<td><strong>AE (°)</strong></td>
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<td>9.88 ± 4.24</td>
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<tr>
<td><strong>BBT (#/min)</strong></td>
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<td>32.22 ± 28.26</td>
<td>8.11 ± 6.81</td>
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<td>Control</td>
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<tr>
<td>Outlier removed (N=8 in each group)</td>
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<tr>
<td><strong>AE (°)</strong></td>
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Table 3: Demographic and clinical data of stroke participants considered for the data analysis (nine participants of the therapy study and nine control subjects). Acronyms: Dom_Hand: Dominant Hand; Aff_Hand: More Affected Hand; TSS: Time Since Stroke (days); 1: Baseline; 2: Discharge; AE: Absolute Error (°); BBT: Box & Block Test (blocks per min); MoCA: Montreal Cognitive Assessment. The control group was built on per-subject basis matching the baseline AE and BBT scores, shown in a matching order in the table. Averages (mean ± SD) are provided above individual values for each group.

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</table>
Figure 1

ETH MIKE robot for the assessment and therapy of hand proprioception.

The platform focuses on the index finger metacarpophalangeal (MCP) joint. It consists of an end-effector of the robot where the finger is inserted and secured using Velcro straps (right image), as well as a tablet computer placed directly above the hand (left image), which displays the graphical user interface of assessments and therapy exercises. The robot can either move the user’s finger (passive tasks) or be actively moved by the user (active tasks). Interaction force, velocity and position signals are recorded via integrated sensors.
Figure 2

Visualization of the graphical user interface of the two example therapy exercises, one passive (Passive Matching) and one active (Active Matching). (a) The goal of the Passive Matching exercise is to choose, on the tablet screen located directly above the hand, among presented options, the location of one's finger after it has been passively displaced by the robot. The choice is made by pressing a button on the touch screen corresponding to the color of the perceived position. (b) In the Active Matching exercise participants need to move their finger as accurately as possible from the starting position (grey needle) to the target position (green needle). (c-d) Visual feedback is provided after every trial.
to facilitate learning. In (c) the pink needle indicates an incorrect answer that was selected by the participant (e.g., orange instead of yellow). A correct answer would be indicated by a needle highlighted in green. In (d) the blue needle indicates the actual finger position, while the green shaded area shows the margin of allowable error.

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### Figure 3

Summary of the study protocol. It consisted of clinical and robotic assessments at baseline (study inclusion) and post-intervention (study discharge), 13 days of robotic therapy (30 min per day, 5 days a week) and usability evaluation conducted every 4 days. Each robotic therapy session consisted of 3 exercises, 2 runs of each, with 15 trials per run. For patients that could actively move their index finger by more than 10° the protocol consisted of a predefined combination of the battery of 5 exercises. For patients who could not actively move the hand due to severe paresis the robotic therapy protocol consisted of a combination of 2 passive exercises (case 2, second row in the table).
Figure 4

(a-e) Performance in each exercise (% of trials with a correct answer) and difficulty levels at which the exercise runs were conducted (1-12). Performance is shown as mean and standard deviation across all stroke participants per exercise run (each run consisting of 15 exercise trials), only considering runs that were performed by all participants (because two participants performed more runs in Passive Matching and Trajectory Perception, but these runs were not considered in plots a-e). The difficulty levels are shown as the average across all stroke participants (N=7 for exercises involving active hand movement, N=9 for passive exercises). A dashed blue line represents the target performance of 70%. (f) Each dot corresponds to the difficulty level per exercise run, one participant per colour. Participants #8 and #13 were highlighted as they performed
only passive exercises, hence more exercise runs were completed by these individuals for the Passive Matching task.

**Figure 5**

Difficulty level increase (b) and exercise performance (a) correlate with improvement in proprioception. A similar trend was observed between performance and change in BBT, when excluding participants with severe hand paresis (c). The exercise performance per subject is taken as the average across all runs and all exercises. The difficulty level is the maximum level reached throughout therapy averaged across all exercises. Abbreviations - AE: Absolute Error, BBT: Box and Block Test, Δ: difference between discharge and baseline assessment score. Numbers next to the data points correspond to participant number. The dashed line represents a linear fit. The rho reported next to the line is the Spearman correlation coefficient.
Figure 6

Results of the raw NASA TLX indicating the perceived task load as indicated by participants (N=9). The smaller the score, the lower the perceived workload. The evaluation was performed every 4 days over the 3 weeks intervention and considering all exercises together as a whole robotic therapy experience. It is desired for the raw TLX values to be below 50% (red line).