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RESEARCH ARTICLE

Robotic task specific training for upper limb neurorehabilitation: a mixed methods feasibility trial reporting achievable dose

Vincent Crocher[a], Kim Brock[b], Janine Simondson[b], Marlena Klaic[c,d] and Mary P. Galea[e]

[a]Department of Mechanical Engineering, The University of Melbourne, Melbourne, Australia; [b]St Vincent's Hospital, Melbourne, Australia; [c]Melbourne School of Health Sciences, University of Melbourne, Melbourne, Australia; [d]Allied Health Department, The Royal Melbourne Hospital, Melbourne, Australia; [e]Department of Medicine (Royal Melbourne Hospital), The University of Melbourne, Melbourne, Australia

ABSTRACT

Purpose: Robotic devices for upper-limb neurorehabilitation allow an increase in intensity of practice, often relying on video game-based training strategies with limited capacity to individualise training and integrate functional training. This study shows the development of a robotic Task Specific Training (TST) protocol and evaluate the achieved dose.

Materials and Methods: Mixed-method study. A 3D robotic device for the upper limb, was made available to therapists for use during neurorehabilitation sessions. A first phase allowed clinicians to define a dedicated session protocol for TST. In a second phase the protocol was applied and the achieved dose was measured.

Results: First phase ($N=5$): a specific protocol, using deweighting for assessment, followed by customised passive movements and then active movement practice was developed. Second phase: the protocol was successfully applied with all participants ($N=10$). Intervention duration: 4.5 ± 0.8 weeks, session frequency: 1.4 ± 0.2sessions/week, session length: 42 ± 9mins, session density: 39 ± 13%, intensity: 214 ± 84 movements/session, difficulty: dn = 0.77 ± 0.1 (normalised reaching distance) and $\Theta=6.3\pm23°$ (transverse reaching angle). Sessions' density and intensity were consistent across participants but clear differences of difficulty were observed. No changes in metrics were observed over the intervention.

Conclusions: Robotic systems can support TST with high therapy intensity by modulating the practice difficulty to participants' needs and capabilities.

IMPLICATIONS FOR REHABILITATION

- Few robotics devices allow for Task Specific Training (TST) of the upper-limb post stroke.
- Robotic TST was shown to be feasible in a clinicians supervised setting.
- In supervised robotic TST sessions, clinicians can modulate task difficulty while preserving similar sessions' density and intensity to adjust to the patient impairment.
- Robotic TST might be used for upper-limb neurorehabilitation without compromising the training intensity.

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Stroke; rehabilitation; upper extremity; therapy; dose; robotics

Introduction

Hubbard et al. define Task Specific Training (TST) as a "training or intervention which utilizes, as its principal therapeutic medium, ordinary everyday activities which are intrinsically and/or extrinsically meaningful to the patient or client." [1] TST, together with intensity of practice, constitutes a core principle of neuro-rehabilitation [2].

While robotic systems for Upper Limb (UL) rehabilitation have seen many developments in the last decades [3, 4] with a focus on increasing therapy intensity, there is minimal use of functional practice components. Most robotic systems for UL rehabilitations are either restricted to planar movements or, when allowing 3D movements, rarely involve the hand or offer practice with everyday objects but are rather coupled to on-screen control of a cursor.

A recent systematic review by Rozenik et al. exploring the effectiveness of TST using assistive devices compared to classic (i.e., manual) TST after stroke, showed equivalent outcomes for chronic stroke patients and a superiority of the assistive approach for patients in the sub-acute phase [5]. Still, it is notable that in this systematic review, the majority of studies (11 of 17) used virtual reality training for TST rather than having participants engage with real life objects and tasks, and that only one of these studies actively supported arm movements [6]. In addition to movement execution and the associated proprioception, eye/hand co-ordination is an essential component of normal human UL function, with bimodal cells of the cortex becoming highly active when the eye and the hand are focused on an object or tool [7]. This aspect of neural function is not evoked with the hand on a cursor or joystick and the eye focused on a screen, as movement emerges from interactions between the individual, the task and the environment [8]. Furthermore, people with neurological dysfunction have difficulty producing appropriate muscle synergies for UL movement, and adapting those synergies to the specific trajectories of movement required to interact with different objects for function [9–11].

The need for robotic training to directly "target all upper limb segments, including the hands" and "work on tri-dimensional

CONTACT Vincent Crocher vcrocher@unimelb.edu.au Department of Mechanical Engineering, The University of Melbourne, Melbourne, Australia
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[against gravity] functional specific tasks which may involve objects" is one main conclusion of a systematic review of RCTs in the field [12]. This need is also clearly expressed by clinicians when asked about the necessary functionalities of robotic systems. In a large clinicians' survey by Lu et al. the two highest rated items reported were "Stroke survivors need task oriented training and practice" and "Stroke survivors need context-specific cognitive learning feedback, and practice." [13] Similarly, based on a literature survey and therapists' interviews, Hochstenbach-Waelen and Seelen conclude that "technology should facilitate repetition of task-related movements, tailored to the patient and patient's goals, in a meaningful context." [14]

Rehabilitation robotic systems (for functional practice or not) often aim to fully automate the process, from the selection of movements to practise to the type and level of assistance to provide. However, this may constitute one of their main limitations. It indeed appears utopian, at least at this stage, to expect a fully autonomous robotic system to be able to define the best practice at every time, for every individual, especially for TST scenarios. Therefore, a key factor in achieving maximum efficacy from robotic training may depend on carefully assessing the movement abilities of the individual and then customising interactions with the robot to build more appropriate and adaptable muscle synergies in tasks. As such it is of interest to investigate how robotic devices can be used as an adjunct to therapists in supervised settings, where these devices can be used to increase the immediate intensity of practice while leaving a large part of the decision-making to the clinician.

A similar approaches of robotic assisted TST have been proposed by Timmermans et al. for highly functional patients using the HapticMaster [6]. However, to date, there are no clear guidelines on how to use robotic systems to assist with TST, and more specifically how therapists can use their skills in movement analysis to customise robotic interactions for improved outcomes. More importantly, it is unclear what intensity of practice can be achieved with such robotic interventions, using goal-oriented task-specific training, in a 3D space. Timmermans et al. pointed out that the complexity of their robotic system may have limited this intensity (which was not reported).

Therefore, in this work, we investigate clinicians' practice with a prototype UL end effector robotic device, the EMU [15]. The EMU was developed through a user-based design process [16], and features include the potential for participants to work with real objects and the ability for clinicians to individually prescribe movement direction and distance in 3D planes with a high degree of specificity. During training, level of assistance provided was determined by the clinician. The EMU was thus used as a system which provided no automation of the movement selection, explicitly requiring the therapist to specify the exact movements to be practiced.

We report the development of a protocol for the use of the robot in functional training, where individuals with neurological disorders practised with direct visual feedback (without screen nor gamification) and with the hand free. In a second phase, the approach is applied with a second cohort of participants and the provided dose is reported following the Dose Articulation Framework [17] and analysed.

Materials and methods

Design

Mixed methods study in two phases.

Setting and participants

Both phases took place in the rehabilitation services of a tertiary teaching hospital. In phase 1, occupational therapists and physiotherapists were invited to participate in the study. For participants with neurological diagnoses, a sample of convenience was utilised for both phases. Potential participants were identified from patients either admitted to inpatient rehabilitation or attending community-based rehabilitation.

Inclusion criteria:

- Adults with a neurologically impaired upper limb
- Medically stable
- Able to follow 1-stage command

Exclusion criteria:

- Unable to provide informed consent
- Severe cognitive deficits
- Severe receptive aphasia
- Uncontrolled epilepsy
- Serious progressive illness

Given the feasibility nature of the study, the inclusion criteria were intentionally kept broad without specific requirements regarding the upper-limb impairment severity either on proximal or distal joints.

All recruited participants (people with neurological disorders and clinicians) provided written informed consent. The study was approved by the Melbourne Health Human Research Ethics Committee (phase 1), and the St Vincent's Hospital Melbourne Human Research Ethics Committee (phase 1 and 2), #2018.067.

Robotic system

The study used the EMU (Figure 1), a 3D manipulandum robotic device, attached to the participant's forearm. A detailed description of the device can be found in Fong et al. [15] and earlier evaluation of usability in Fong et al. [16] and Klaic et al. [18]

Within this study, three different modes of assistance, depicted in Figure 2, were available on the robotic device:

- De-weighting (or gravity compensation) mode, where the robot provides a constant, adjustable vertical force at the forearm attachment point, otherwise leaving free movement of the hand.
- Passive mobilisation mode, where the robot fully drives the movement of the participant's forearm from an individually specified path from A to B in a predefined time. The participant may remain completely passive during completion of the movement.
- Corrective mode, where the device constrains the movement from A to B, preventing any movement initiation and progression outside of a virtual rigid tunnel. This is a different function to path guidance that is available on many robots where the movement path is redirected by the robot into the correct path as a response to participant error. In this mode, an optional variable assistance (a positive damper) can be added to assist towards task completion, once the movement has been initiated. Note that in this mode, to avoid slacking, the patient still needs to initiate and continue the movement close to the specified direction.

Figure 1. Illustration of the setup of a typical session with examples of practice when the person has hand function (top-row) and without hand function (bottom row). Bottom left picture shows how therapists prescribe the practice movements. Note the use of a perching stool for seating to optimise postural activation.

Phase 1

Measures

Prior to commencing robotic training, participants with neurological disorders were evaluated using the WHO Disability Assessment Schedule 2.0 [19] (12 items version) and the upper limb components of the Motor Assessment Scale [20].

Clinician feedback about the session was collected using an ad-hoc questionnaire (see online supplement).

An iterative process of engineering development was applied. Based on therapists' feedback and observations, modifications of the device software and hardware were implemented during this first phase.

Procedures

Therapists involved in the first phase were trained to use the robotic device during a 30-min session lead by an engineer researcher (VC). Following this training, clinicians conducted six one-hour therapy sessions with individual participants.

Prior to attaching the participant's forearm to the robot, the clinician assessed the individual's control of movement of the

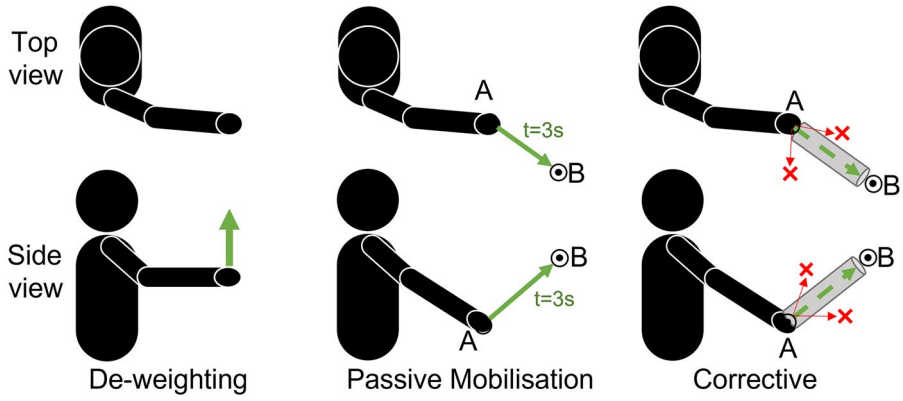

Figure 2. The three interaction modes available on the robotic system. Robot actions on user's hand are depicted with green arrows and grey tunnels indicate the accuracy of movement the user must meet to initiate and complete the movement.

shoulder, elbow, wrist and hand with regard to range of movement available, active movement control and presence of spasticity. Ability to interact with objects was assessed using everyday items. The participant and clinician together identified a functional goal of importance to the participant and realistic to their current level of ability. The postural alignment and stability of the participant were also evaluated and appropriate seating to optimise postural control determined.

With the robot connected, individual movement synergy deficits for reaching were evaluated using the Deweighting mode. Sub-movements requiring specific training were identified, aiming for a movement trajectory close to, but beyond, the individual's current abilities. The clinician then used the device with its various interaction modes, to train relevant movements and tasks. Clinicians defined the movements and sub-movements to practice by simply demonstrating and registering the start and end points using a touch screen interface. Figure 1 shows a typical session setup. Participants completed six one-hour sessions with the robot over a three- to six-week period.

Given the prototype nature of the device, an engineer researcher (VC) attended each session to ensure safe use of the robot and to identify issues that arose in terms of the engineering specifications and the tasks the clinicians wanted to achieve with participants. Possible risks included malfunctions (e.g., no response to a command), unexpected stops (or failed-mode activation) or unexpected movements of the device which could require intervention from the engineer to evaluate the problem and to ensure conditions were safe before resuming the session.

A clinician researcher (KB) involved in the design of the EMU attended most sessions, assisting clinicians to identify potential use of the robot for each individual.

Phase 2

Measures

Before the first robotic therapy session, participants were evaluated with the WHODAS 2.0 and the MAS (upper-arm and hand components).

During the sessions, a TrakSTAR 3D Guidance Magnetic Sensors (Ascension Technology Corporation, USA) was used to measure the subjects' shoulder, elbow and wrist positions and orientations. In addition, the robotic device logged the settings used and wrist movements. Data collected were then processed using custom Python scripts to obtain the dose metrics.

Procedures

Therapists involved in the second phase were introduced to the robotic device and the protocol developed in phase 1 before conducting therapy sessions. The same engineer was present during the therapy sessions as in phase 1.

Participants with neurological injury were offered six one-hour therapy sessions, scheduled twice a week. Sessions followed the protocol developed in phase 1.

Dose reporting

Following the Dose Articulation Framework [17], the dose was measured and reported along six dimensions:

- Duration – time between first and last session (weeks);
- Session frequency – number of sessions per week of intervention;
- Session length – overall session time including set up (minutes);
- Session density – moving time: percentage of session time with the hand moving;
- Session intensity – number of movements (defined as point-to-point straight lines) performed during a session;
- Task difficulty – (a) normalised reaching distance d_n (0: hand on shoulder and 1: full arm extension), (b) angle Θ (degrees) of the Wrist-Elbow-Shoulder plane projected onto the transverse plane (positive: external, negative: internal), in Corrective mode.

Descriptive analysis of the density, intensity and difficulty measures were then performed. Spearman's correlation coefficient between each of these metrics and the session number as well as the patients' impairment level (measured as the MAS arm + hand components scores) were calculated.

Results

Phase 1 – protocol development

Participants

Five clinicians, three physiotherapists and two occupational therapists were trained to use the device and participated in phase 1.

Five participants with neurological disorders were included in this phase and used the device for functional training. Due to

COVID restrictions, this phase was interrupted before completing the recruitment and before all included participants could complete the six sessions specified in the protocol. The fifth participant recruited to the study could not participate due to a device malfunction in the first session, followed by discontinuation of the study due to COVID restrictions. Data from this participant have been excluded from all subsequent analyses. The demographics and clinical assessments, for the four included participants are shown in Table 1.

A total of 22 sessions were conducted for the four participants, with two participants completing the planned six sessions and two completing five sessions.

Key clinical observations

With all participants, training of sub movements was undertaken prior to engaging with objects for TST, due to difficulty reaching or the presence of aberrant movement patterns. Movements trained usually commenced with the participant's hand resting comfortably close to the body and towards the midline. Sub-movements practised included reaching forward with extension of the elbow, moving the hand away from the body, e.g., from midline towards abduction/external rotation at tabletop height, reaching forward and up towards shoulder level to different points in space and taking the hand to the mouth. The Passive Mobilisation mode was utilised to enable the participant to sense and perceive the movement to facilitate more accurate feedforward commands, followed by the Correction Mode, with or without assistance. Where participants were unsuccessful at initiating the movement trained, repeated attempts often yielded success, or an easier movement was trained. The Deweighting Mode was used intermittently during each session to explore more difficult trajectories/distances to train. For object-based task training, tasks with varying levels of complexity were utilised: knocking over tissue boxes, pushing containers or balls across the table, picking up and moving an object ball or container, and taking a drink bottle to the mouth. Whether training focused more on sub-movements or on use of objects was determined by both the clinicians, according to the participant's ability, and by the participant's preference. Participants were often motivated to practise movements they knew they could not do (e.g., straighten the arm to reach) as sub-movements, moving onto object-based training later in the session.

Clinicians used hands-on interventions intermittently during the robotic training (e.g., drawing attention to compensations of the trunk or facilitating movement at the elbow, wrist or fingers). Adapted seating was utilised in 20 sessions, including perching stools and modified wheelchair seating. The robotic device was used in standing for seven sessions. As sessions progressed, a systematic approach to prescription of robotic therapy was developed (see online supplement).

Table 1. Demographic and clinical data of participants.

		Age/ Gender	Diagnosis	TSO (weeks)	Dom. hand	MAS arm (/6)	MAS hand (/6)	WHODAS 2.0 – 12 items (/48)
Phase 1	1	47/M	L MCA infarct	28	Yes	1	0	17
	2	77/F	Multiple Sclerosis (stable)	245	Yes	3	3	38
	3	44/M	L Basal ganglia ischaemic stroke	63	Yes	3	0	31
	4	57/M	L Subcortical infarct	48	Yes	1	0	38
Phase 2	5	60/M	L MCA infarct	988	Yes	3	3	25
	6	77/F	L Thalamic infarct	3	Yes	5	3	38
	7	33/M	L Pontine infarct	46	Yes	5	5	14
	8	39/F	R Basal ganglia haemorrhage	294	Yes	1	0	18
	9	78/F	L MCA infarct	87	Yes	0	0	16
	10	68/M	R subcortical infarct	12	No	3	4	9
	11	80/F	L subcortical infarct	12	Yes	2	1	17
	12	58/M	TBI - Bilateral intracerebral haemorrhage	34	Yes	5	5	9
	13	66/M	L Basal ganglia haemorrhage	465	Yes	1	0	11
	14	68/M	R MCA CVA infarct & haemorrhage	465	No	0	0	21

TSO: Time since onset, MAS: Motor Assessment Scale (where 0 = unable to perform any of the specified activities to 6 = optimal motor behaviour), WHODAS 2.0: World health organisation Disability Assessment schedule 2.0 – 12 items version (where 0 = no disability to 48 = full disability).

Clinicians' perceptions of the utility of the EMU

Feedback from clinicians supported the utility and useability of the EMU, details of these findings are provided in the online supplement.

Iterative evolution of the EMU

In terms of perceived limitations of the system identified by clinicians and investigators, the following additional features or functionalities of the system were implemented:

1. Capacity to prescribe complex movements made of multiple linked sub-movements (e.g., reach for a cup and drink).
2. Capacity to finely tune the quantity of assistance (positive damping) in the Corrective mode on a sliding scale.
3. Capacity to provide additional limb support beyond the end effector unit. This varied from a simple extended end effector support to maintain wrist alignment to utilising the Saebo glove (Saebo, NC, USA) to assist with finger extension while picking up objects.

Phase 2 – dose evaluation

Ten additional participants were recruited for the second phase of the study (Table 1), and all participated in six sessions following the protocol developed in phase 1. Intervention duration was 4.5 weeks (SD = 0.8 weeks) with a frequency of 1.4 sessions/week (SD = 0.2), and session length of 42 min (SD = 9 min).

Session density (Figure 3) as measured by the percentage of moving time was 39% (SD = 13%). The mean for each participant varied from 30% (P11) to 47% (P14). The mean for the first two sessions and last two sessions where 36% and 39% respectively. No significant correlation between the density and either the session number or the participants' MAS scores was found (Table 2).

Session intensity (Figure 3), measured by the number of movements (mvts) per session, was 218 movements (SD = 83). The mean for each participant varied from 168 (P6) to 294 (P7). The mean for the first two and last two sessions were 203 movements and 224 movements respectively. No significant correlation

between the intensity and either the session number or the participants' MAS scores was found (Table 2).

Difficulty of the different sessions for each participant is depicted in Figure 4. The area of practice was focused for individuals across sessions but clear differences, both in terms of reaching distance and (d_n) arm-plane angle (Θ), were observed between the different participants. None of the metrics were correlated with the session number but there was a moderate positive correlation between both difficulty metrics and the participants' MAS scores, which were statistically significant (Table 2).

In terms of robotics interaction, the three modes of interaction offered by the device were used in all but one session (P5, S1). The Passive mobilisation mode was the most used (36% of movement distance), followed by the De-weighting mode (33% of movement distance) and the Corrective mode (30% of movement distance).

Discussion

Overall, this study confirms the findings of previous studies [5], including those of Timmermans et al. [6] that robotic devices designed for and aiming at task-specific practice constitute a feasible approach. The current study shows that such an approach can be integrated into clinical practice in a real-world context, as an alternative approach to gamification or virtual reality. The use of everyday objects in robotic training engages other brain functions in addition to movement execution, requiring engagement of the perception/action paradigm in context, to assess the characteristics of the object and organise the appropriate motor plan to complete the task. The inclusion of TST in robotic training may be a promising direction to counter the limited translation of robotic intensive training to functional outcomes [21]. The robotic assistance used here offered the possibility of achieving a relatively high practice intensity and providing insights on the actual dose achieved.

Potential benefits from tailored prescription of movement trajectories and tasks

The approach taken in this study focused on individual prescription of robot-assisted movements, in contrast to pre-set robotic programmes that are less able to take into account the individual specific abilities and to tailor the training towards a specific functional goal. Few studies have investigated individualised performance-based selection of robotic practice movements [22]. The conceptual basis of this approach was to focus on improving motor synergies to more accurately match motor output to specific movement trajectories.

Once a trajectory (direction and distance) was selected, then the passive movement condition was utilised for exact repetition of the movement, providing both proprioceptive and visual cues for feedforward planning. The corrective mode required the participants to activate and adapt muscle synergies to perform the selected movement, i.e., participants were aware of both successful trials and errors. Within the corrective mode, assistance could be adjusted, following an assist-as-needed paradigm [23], to complete the movement trajectory. In this way, appropriate activation of muscle synergy components, though sometimes insufficiently strong to complete the movement, still resulted in the completion of the specified task.

Initial training generally focused on sub-movements (customised, co-ordinated elbow and shoulder movements) where participants could not perform functional reach movements or performed reach movements with aberrant movement patterns. As control of sub-movements improved, the sub-movements were incorporated into more functional tasks, similar to the approach used by Daly et al. [24].

An iterative process then enabled extension of direction, distance and complexity of trajectories, in accordance with the view expressed by Hogan et al. that "progressive training based on measures of movement coordination yields substantially improved outcomes." [25](p06).

Interestingly, where the individual could not initially achieve the movement within the constraint of the corrective mode, repeated attempts usually resulted in success. This may reflect the capacity of the CNS, including cerebellar functions, to use trial and error to find the correct motor output when the error is small, i.e., attempts are close to the required trajectory [26]. This highlights the importance of accurate assessment to prescribe a movement trajectory that is near to a patient's current abilities and then build on this sequentially. In addition, following the feedback-feedforward motor adaptation paradigm [27], it is expected that when only an accurate initiation results in movement, the feedforward will be further refined and reinforced based on the feedback from the actual movement. This process will be effective where the corrective mode is used as a strict constraint, only allowing

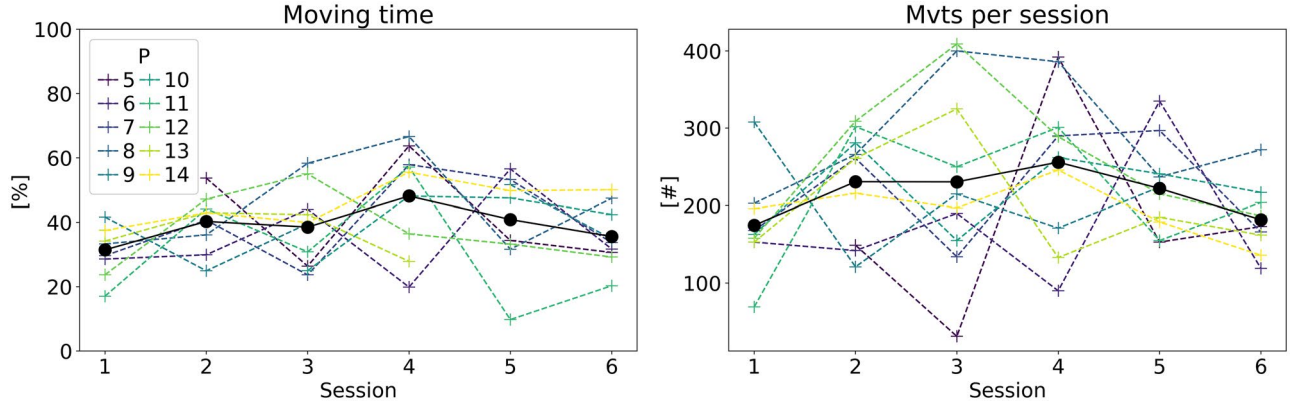

Figure 3. Session density reported as the percentage of time with hand moving (left) and session intensity reported as number of movements (mvts) per session (right).

movement when initiation is appropriate, and not effective where a robotic guidance would actively correct a wrong initiation (and so would reinforce the internal model based on an inappropriate feedback). In the review of robotic devices control approaches by Basteris et al. only 3 of the 28 devices focusing on proximal arm control included a correction mode [4].

While the GENTLE/S project [28] and later work by Timmermans et al. [6] have similarly provided movement correction for 3D reaching movements and showed interesting results, they did not attempt to combine this approach with a customisation of the training trajectories nor to align this training to task practice (and so closer to the patients' functional goal). Indeed, their approach used on-screen activities (e.g., within a virtual environment) and predefined set of trajectories. We thus here show the feasibility of this customisation on task-oriented movement, while preserving the robotic interest of consistently providing guidance and correction to the patient and allowing a large number of repetitions.

Table 2. Spearman's correlation of the different metrics with the session number and the participants' MAS score.

		Session number	MAS Score
Density	Correlation coefficient	0.13	−0.16
	CI (95%)	[-0.13 0.36]	[-0.35 0.15]
	Sig. (2-tailed)	0.32	0.25
	N	55	55
Intensity	Correlation coefficient	0.03	0.01
	CI (95%)	[-0.24 0.27]	[-0.26 0.25]
	Sig. (2-tailed)	0.84	0.96
	N	58	58
Difficulty (d_n)	Correlation coefficient	0.09	**0.55*****
	CI (95%)	[-0.13 0.37]	[0.32 0.70]
	Sig. (2-tailed)	0.43	<0.001
	N	52	52
Difficulty (Θ)	Correlation coefficient	−0.04	**0.46*****
	CI (95%)	[-0.32 0.19]	[0.06 0.53]
	Sig. (2-tailed)	0.76	<0.001
	N	52	52

Note the variable number of samples for the different metrics due to missing data in some sessions.

Intensity of practice and difficulty modulation

Despite the absence of games for motivation and the demanding conditions of having to find the "right" movement for success, once the protocol was established (phase 2), participants were able to achieve a high number of repetitions per session with a mean of 218 movements. This is notably above standard clinical practice which has been reported to be 32 repetitions [29]. To successfully extend the elbow as a result of their own initiation of movement, when this had not been possible, was highly motivating to individuals with severe UL deficits. Therefore, this approach to robotic training is able to deliver the intensity of training sought from robotic devices. It is a notable difference from the study of Timmermans et al. which reported that the robotic system complexity may have limited the number of repetitions provided while using the robotic device [6].

Neither density nor intensity measures showed any large change over the intervention period and while session density was relatively consistent across all participants (min. 30% and max. 47% of moving time), the intensity measure (number of movements) showed variation of up to 1.75 times between participants. Still, no trend could be established based on participants' MAS score, suggesting that participants at different levels of ability could participate successfully.

Similarly, the difficulty of the tasks practiced (i.e., normalised reaching location) was found to be consistent over the intervention. Clear correlation of both difficulty metrics with participants MAS score were established. This suggests that the therapists choose to modulate the difficulty based on each individual participant capabilities (with further and more external movements with less-impaired participants).

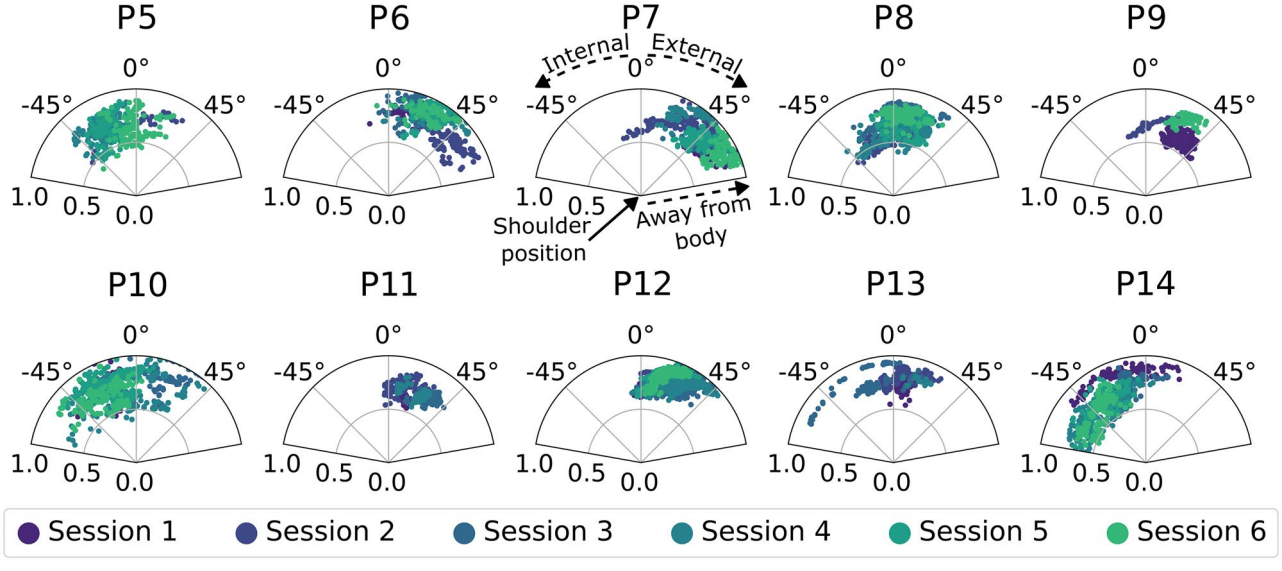

Figure 4. Difficulty in each session reported as reaching distance versus arm-plane angle for each participant and all sessions. Each dot corresponds to a movement practiced in corrective mode (i.e., patient actively contributing to the movement).

Limitations

The observations reported in this study have been influenced by the specific design of the EMU robot used and the capabilities built in. As such, a full generalisation to any robotic system with close but different capabilities (such as different interaction modes or different workspace) may be limited.

Similarly, the dose reporting was made possible by the robotic device and sensors used in the study. However, to report the dose following the Dose Articulation Framework, choices of specific metrics were made. While the reporting of the training duration, sessions frequency and sessions length is straightforward, the reporting of the session density, intensity and task difficulty is more ambiguous and tailored to the approach taken (e.g., what type of movements are performed, in which context) and the available data. It is also noted that for the purpose of the analysis, the two complementary difficulty metrics have been considered independent. While a correlation may exist (indeed, it is likely that some relationship between them exist in the way therapists prescribe training movements), no simple relationship between the two could be modelled. As such, it not surprising that if one metric does show a correlation with the MAS score, the other shows a similar correlation.

It is also acknowledged that in this study, an engineer was present during each therapy session to provide ad-hoc support. While this is unrealistic in a clinical implementation, it is to note that, during the second phase of the study (evaluating the approach), these interventions were limited, mostly to introduce new features added to the device and to provide confirmation of feasibility of a given feature to the clinician. While not formally documented, it was observed that such interventions and advice were mostly present during the first sessions of each therapist and very little (if any) after the second of third session of each therapist. This suggests that this support can be avoided with a more formal training of the clinicians as well as more robust and consistent design of the device.

Additionally, in terms of trajectory, only the transverse plane is considered, whereas movements occurred in 3-dimensional space from tabletop to shoulder height, affecting the task difficulty in practice. Difficulty of the task can also be modified by changing the amount of assistance provided, by incorporating several trajectories into one movement activity and by involving objects requiring activation of the wrist and hand. Difficulty is thus a complex, multidimensional but important component of dose to capture.

Finally, no clinical outcomes regarding movement performance or function or level of assistance by the robot or participant experience were measured in this study.

Future research directions

Observation of the training sessions suggests that participants improved in their ability to control movement trajectories both while working with the robot and after the session without robotic assistance. Measurement systems for evaluation of these changes in the clinical setting need to be investigated. This should also be complemented by evaluation of outcomes on real-world task performance, possibly through participation type measures.

This study explored the use of TST in one-on-one supervision of training sessions. Once an individual has improved trajectory control from one-on-one sessions, it may be possible to use the robot with distant supervision to practice what they have achieved.

Conclusion

Robotic systems using TST, inclusive of sub-movement training, may be a useful addition to robotic training programs. The prescription of movement trajectories near to the ability of the individual, together with the corrective mode constraining movement to appropriate muscle synergies for the specified trajectory, may be a new approach to recovery of UL movement control. High intensity of TST can be achieved with such an approach while the task difficulty can be modulated and tailored to the patient. This type of robotic training and its clinical efficacy should be further investigated, particularly at the early stage of recovery where these devices offer an opportunity to significantly increase practice intensity and engagement in individuals with varying levels of upper limb function.

Author contributions

VC, KB, MK and MG developed the study protocol. VC, KB and JS performed the data collection. VC and KB analysed the data and drafted the manuscript. All authors reviewed and edited the final manuscript.

Disclosure statement

VC, is a co-inventor of the EMU device (patent WO/2018/213896), now commercialised by Fourier Intelligence (Shanghai, China).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, VC, upon reasonable request.

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