Designing an app for home-based enriched Music-supported Therapy in the rehabilitation of patients with chronic stroke: a pilot feasibility study

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Objective: After completing formal stroke rehabilitation programs, most patients do not achieve full upper limb motor function recovery. Music-supported Therapy (MST) can improve motor functionality post stroke through musical training. We designed a home-based enriched Music-supported Therapy (eMST) program to provide patients with chronic stroke the opportunity of continuing rehabilitation by themselves. We developed an app to conduct the eMST sessions at home with a MIDI-piano and percussion instruments. Here, we tested the feasibility of the eMST intervention using the novel app.

Method: This is a pilot study where five patients with chronic stroke underwent a 10-week intervention of 3 sessions per week. Patients answered feasibility questionnaires throughout the intervention to modify aspects of the rehabilitation program and the app according to their feedback. Upper limb motor functions were evaluated pre- and post-intervention as well as speed and force tapping during daily piano performance.

Results: Patients clinically improved in upper limb motor function achieving the Minimal Detectable Change (MDC) or Minimal Clinically Important Difference (MCID) in most of motor tests. The app received high usability ratings post-intervention.

Conclusion: The eMST program is a feasible intervention for patients with chronic stroke and its efficacy should be assessed in a clinical trial.

Keywords: Chronic stroke; Telerehabilitation; Music-supported therapy; Motor function

Introduction

Stroke is the leading cause of acquired long-term disability worldwide (1). Over fifty percent of stroke survivors have motor function impairments and require support, especially with instrumental activities of daily living (1-4). The residual functional limitations in the upper limb cause difficulties with day-to-day physical and social activities affecting emotional well-being and quality of life (QoL) (5, 6). Therefore, engaging in rehabilitation programs based on promoting adaptive motor learning is critical for patients with stroke to restore motor functions as well as autonomy in daily life (7-11). Patients usually undergo formal rehabilitation programs during the first six months post stroke to take advantage of the increased plasticity period during the subacute phase (9, 12-16). However, after this six-month rehabilitation period, most patients do not achieve full recovery of upper limb motor function (17). Moreover, patients with chronic stroke can suffer a decline in their motor functions due to the decrease in their physical activity after completing the rehabilitation program (18-20). This may be related to the absence of an active routine previously provided by attending regular therapist-led sessions (21). Hence, the need to create more accessible rehabilitation programs has emerged in order to maintain or improve motor function in patients with chronic stroke (22).

Musical training is increasingly recognized as a useful tool to enhance motor and cognitive functions as well as QoL in patients with stroke (23). Musical activities provide a multimodal experience that requires the simultaneous activation of different brain areas. These areas are involved in sensory-motor function, auditory processing, emotional processing, and cognitive functions such as memory and attention (24, 25). When playing a musical instrument, the immediate auditory feedback provided by the instrument is used to adjust future movements and reinforce motor learning (26-28). Musical training can provide enjoyment, stress relief, and distraction from negative cognitive states and from physical effort (24, 29, 30). Moreover, learning to play an instrument involves acquiring a new skill set enabling patients to gain a sense of competence (28). These effects can feed intrinsic motivation to adhere to motor exercises in which music is present (31).

Music-supported Therapy (MST) is one of the most investigated rehabilitation techniques based on musical training. It consists of playing musical instruments with the paretic upper extremity to improve both fine and gross motor functions post stroke (32). This intervention is based on the principles of massive repetition of upper-limb movements, audio-motor coupling, shaping according to the individuals' progress, emotion-motivation effects, individualization of the program, and increase of exercise complexity (23, 28, 32). MST sessions are usually provided by a therapist at the hospital or rehabilitation center, where patients play simple sequences with an electronic keyboard and/or rhythmic sequences with drum pads. MST has been shown to be effective in the rehabilitation of upper-limb motor function after stroke (32-34) as well as in promoting cognitive and QoL improvements (35, 36). In a pioneering study in 2007, Schneider et al. (32) conducted a randomized controlled trial (RCT) about MST. In comparison to the control group, patients treated with MST demonstrated significant improvements in speed, motor control, precision and smoothness of their movements (32). Recently, Grau-Sánchez et al. (36) conducted a RCT where both MST and control groups demonstrated improvement in motor function but only the MST group showed significantly higher QoL. The motor function improvement was found to be associated with the ability to experience pleasure from musical activities (36).

One of the aims of stroke rehabilitation in the chronic phase is to develop and maintain maximum autonomy in order to facilitate participation and reintegration into community life (37). Conducting home-based non-therapist-led sessions encourages patients to engage in self-regulated behaviors throughout the learning process, which can lead to a greater recovery according to motor learning theories (38-41). This can help patients to develop autonomy by increasing participation in the chronic phase (21). In this line, telerehabilitation (TR) is an emerging modality of intervention and a promising option for patients with chronic stroke to conduct rehabilitation programs at home with greater independence (42). Knepley et al. (42) conducted a systematic review of 34 studies regarding stroke TR. They concluded that TR can be as effective as conventional hospital-based rehabilitation at improving motor and cognitive functions as well as QoL post stroke. They observed the following advantages: several application forms of therapy; ability to be delivered effectively in community settings; possible combination with hospital-based rehabilitation; increase of accessibility and decreased costs; and possibility of communicating and assessing patients' feelings (42).

We designed an enriched MST (eMST) program to provide patients with chronic stroke with the opportunity of continuing rehabilitation at home. In this way, they could continue to improve motor functions once they have completed their formal rehabilitation program. We developed an app for electronic tablet to conduct the sessions at home together with a MIDI-piano and different percussion instruments (43). In order to achieve an active engagement from patients, the app incorporates the following features based upon previous MST programs: 1) continuous monitoring of therapy activities, 2) personalization of exercises adjusting the difficulty levels to patients' progress and needs, 3) incorporation of positive feedback and gamification strategies to enhance patient adherence and learning, and 4) empowerment of patients to self-regulate their training sessions (43). The main goal of the present study is to assess the feasibility of the home-based eMST program using the novel app. This was done before conducting a randomized controlled trial (RCT) in order to avoid potential issues when testing the effectiveness of the eMST intervention. Firstly, we wanted to ensure the usability of the eMST app through which the home-based intervention is provided. In order to obtain the maximum usability, we aimed to improve the first version of the app over the course of the study using patients' feedback and first-person experience. We also aimed to test the motor function gains, the intervention adherence and the safety to increase clinical experience and enhance the likelihood of success when applying the eMST intervention on a larger scale.

Materials and methods

Participants

The recruitment was done by advertising the pilot study in a non-profit stroke patients' association in Barcelona (Spain) that has approximately 70 members. Four female patients and one male patient with chronic stroke contacted with us via telephone to participate in the study. After doing individual interviews at the hospital to assess whether they fulfilled the inclusion criteria, the five patients were subsequently accepted to participate (mean age 52.6 years ± 13.3; mean time since stroke 3 years and 8 months ± 36.38). The inclusion criteria was the following: 1) more than 6 months post-stroke, 2) presence of mild-to-moderate paresis of the upper extremity post stroke (having a score between 1 and 4 in the Medical Research Council Scale for Muscle Strength at the distal muscles of the upper extremity), 3) not doing rehabilitation at the time of recruitment, 4) no major cognitive deficits affecting comprehension (Mini-Mental State Examination > 24), 5) no neurological or psychiatric co-morbidity, with exception of post-stroke depression, and 6) no other musculoskeletal condition affecting upper extremity motor function (e.g. fracture or arthritis).

A sample of 20 healthy participants (10 females, mean age = 63.5, *SD* = 8.77; 10 males, mean age = 65.3, *SD* = 6.85; with no significant difference in age between gender, $F = .262$, $p = .615$) were recruited as a control group to establish piano performance baseline values. They showed no neurological or psychiatric co-morbidity, nor any musculoskeletal condition affecting upper extremity motor function. Patients' improvement could be checked by comparing their values with healthy controls performance values throughout the intervention.

The protocol of this study was approved by the Clinical Research Ethics Committee of the Bellvitge University Hospital (PR095/17; Barcelona, Spain) and the Hospitals del Mar i l'Esperança (Parc de Salut Mar, 2020/9523; Barcelona, Spain) and follows the Declaration of Helsinki to experiment with human beings (45). Participants signed an informed consent prior to participation explaining the feasibility objectives of the study and the absence of potential risks for completing the eMST intervention.

General procedure

Patients followed a 10-week eMST intervention using the novel app consisting of 3 sessions per week. They did 30 sessions of varying length as the number and time of percussion exercises were modified over the study to adjust the session length to 1h approximately. The first three recruited participants completed the first 15 sessions in the hospital with a music therapist, and the rest of the sessions at home alone. This was done to check that the first version of the app worked properly the first-time it was used by patients. In the first session, the music therapist showed the functionality of the electronic tablet and the app. In subsequent sessions at the hospital, she checked that patients were able to do the self-training sessions on their own and that the app did not have any technical glitches. During hospital-based sessions, the music therapist took notes of patients' feedback regarding some problems they may encounter (e.g., small font size, low volume, etc.). The other two participants completed the whole intervention at home alone, only doing the first session with the music therapist in order to learn how the tablet and the app work. The music therapist visited their homes to provide them with all the necessary materials for the intervention: an electronic tablet with charger, a MIDI-piano keyboard with a tablet connection cable, and a box with percussion instruments. Throughout the course of the home-based sessions, the music therapist remotely monitored patients' engagement and performance by weekly phone calls and checking the app inputs through the eMST website program.

App development

In order adapt the eMST program for home use, a multidisciplinary team of engineers and therapists worked together to create an app (43). Firstly, the therapists checked which of the musical exercises from the original MST program were the most appropriate for the eMST program. It was decided to introduce the original piano exercises and to add percussion exercises played with eight percussion instruments alongside the commonly used electronic drums. Each percussion exercise was designed considering the upper limb movements currently performed in conventional interventions (without music) (44). Engineers and therapists collaborated on how to display the different exercises on the app whilst considering the technical constraints of doing so. Technical aspects encompassing the type of instructions, stimuli and feedback display, and inputs registered were also discussed. Video tutorials were recorded and added onto the app to display the instructions of how to play the percussion instruments. Gamification and telematic monitoring elements were also introduced to create an app based on reinforcing motor learning components (43). Throughout this study, the technical features of the first version of the app were changed according to patients' feedback obtained from the notes took by the music therapist in the hospital-based sessions and usability questionnaires answered post-intervention. For more details of the development and functions of the eMST app, please see the study by Sanchez-Pinsach at al.2019 (43).

Intervention

The eMST intervention consisted of individual self-training sessions using an app on an electronic tablet. The app provided instructions on all of the exercises, recorded patients' MIDI-piano performance, and gathered data regarding engagement and length of session. Each session was organized into two main parts: 1) playing percussion instruments to warm up the affected upper limb and train gross motor skills, and 2) playing the MIDI-piano to train fine motor skills. Below is the outline of both percussion and piano exercises. Please see methods on the study protocol by Grau-Sánchez et al., 2021 (45) for more details.

The percussion exercises consisted of playing with the affected limb rhythmic patterns with four different percussion instruments in each session. Patients were asked to play each rhythmic pattern with a specific tempo depending on the exercise level (from 1 to 8), the instrument, the movement suggested to play it, and their level of motor impairment. Eight different percussion instruments were selected to play these exercises: tambourine, tambourine with beater, djembe, maracas, egg shaker, rainstick, castanets, and guiro. The app displayed the instructions on the tablet for the percussion exercises including the presentation of the instruments and movement tutorials (see *Figure 1A*). *[Figure 1 near here]*.

The piano exercises consisted of playing different note sequences with a MIDI-piano using different fingers or combination of fingers with the affected hand. The sequences were formed by white key notes and were classified into 9 difficulty levels. To perform the piano exercises, instructions were displayed on the tablet including the presentation of the hand and finger/s that were to be used and the sequence of notes to be played (see *Figure 1B*). When patients played an incorrect note, it was marked in red to make them aware of the mistake and allow for self-correction. More feedback was presented to motivate patients to play as best they could: a scoring system with numbers that increased as the participant followed the exercise; and a pie chart displayed at the end of each session with the proportion of correct and incorrect notes. To check piano performance progress, patients did two piano evaluation exercises after their daily exercise series over the 30 sessions. The evaluation exercises consisted of playing the simplest sequence of the two easiest levels of the piano exercises (see *Table 1*). Before finishing the session there was the option of playing a game called *Simon*, where a sequence of notes was progressively presented and should be repeated one by one. *[Table 1 near here]*

Main study objectives

The main study will be a RCT aiming to test the effectiveness of the home-based eMST intervention in improving upper limb motor functions in patients with chronic stroke when compared to a validated conventional home-based rehabilitation program. Secondary objectives will be to assess cognitive functions, QoL, emotional well-being, as well as self-regulation and self-efficacy behaviors. We hypothesize that participants undergoing the eMST intervention will demonstrate greater motor and cognitive improvements, and enhanced QoL, emotional well-being and self-regulated behaviors when compared to participants undergoing the conventional intervention (Grau-Sánchez et al., 2021).

Main study outcomes

The primary outcome of the main study is the functionality of the paretic upper extremity measured with the *Action Research Arm Test* (46). Secondary outcomes include other motor and cognitive functions, emotional well-being, and QoL measures as well as self-regulation and self-efficacy outcomes. Please see methods on the study protocol by Grau-Sánchez et al., 2021 (45) for more details.

Feasibility and usability

The feasibility of the eMST intervention and the usability of the app were assessed using two questionnaires together with patients' feedback collected throughout the hospital-based sessions and telematic monitoring. The feasibility was measured using a structured interview at weeks 1, 5 and 10 of the intervention. The interview questions were focused on patients' opinion about different aspects of the rehabilitation program including: total duration of the sessions; time per exercise; difficulty level of exercises and movements; comfort level using the app; comfort level using the instruments; and feeling of tiredness. In this structured interview some questions about the usability of the app were included. These questions were focused on patients' opinion about technical aspects of the app such as whether the volume, instructions and visual appearance were appropriate, and if the feedback was noted.

The usability was measured using *The System Usability Scale (SUS)* (47). This questionnaire consists of 10 items with a 5-points score (from *1: Strongly disagree* to *5: Strongly agree*) regarding the convenience of using new devices and applications. Participants were asked to answer this questionnaire post intervention to check whether they would use the app again and to which degree.

Clinical evaluation

To evaluate patients’ motor function, the following motor outcomes were obtained pre- and post-intervention: 1) functional movements such as grasping, gripping and pinching were measured using the *Action Research Arm Test* (46), 2) motor impairment was measured using the *upper extremity subtest* of the *Fugl-Meyer Assessment of Motor Recovery after Stroke* (48), 3) hand and finger dexterity were evaluated using the *Box and Block Test* (49) and the *Nine Hole Pegboard Test* (50), and 4) motor performance in activities of daily living was assessed using The *Chedoke Arm and Hand Activity Inventory* (51).

Piano performance

To evaluate patients’ piano performance, the app was set to collect the information from the MIDI-piano which was connected to the electronic tablet as a MIDI-device. Patients’ performance was assessed in every session by recording played notes, errors, inter-note time, key-pressure, and execution time for all the exercises. The percussion exercises could not be evaluated when they were performed at home because the app only collects data generated on a MIDI-device.

To analyze patients’ piano performance, three variables related to speed and force tapping were selected: 1) execution time or total duration of each evaluation exercise measured in milliseconds, 2) inter-note time or time between notes played in each evaluation exercise measured in milliseconds, and 3) pressure applied on the keys in each exercise, codified as the velocity with which a key is pressed from 0 to 1.

To check the improvement in performance over the intervention, baseline values were established from control participants’ piano performance. Patients' values were compared to baseline values to monitor whether and when they approached healthy controls performance.

Intervention adherence and safety

Patients' adherence to the eMST intervention was evaluated by comparing what was planned (completing 30 self-training sessions in 10 weeks) to what each patient did. Patients were asked to complete 3 sessions per week regardless at which day of the week and at what time were completed. To check the safety of conducting self-training eMST sessions at home alone, the therapist who monitored them remotely by phone calls asked them and took notes weekly about any adverse effects during the week (e.g., muscle pain, headache, joint pain, etc.).

Feasibility criteria

To evaluate the success of feasibility, we stated the following criteria: the usability questionnaires scores should be equal to or higher than 3 (and equal to or lower than 3 in the negative statements); the participants should complete all the sessions (a total of 30) in 10 weeks; the difference between the pre- and post-evaluation motor tests scores should achieve the Minimal Detectable Change (MDC) or the Minimal Clinically Important Difference (MCID); the speed and force tapping variables should achieve or be closer to the controls piano performance at some point over the whole intervention; the completion of the home-based intervention should not demonstrate potential risks for patients health.

Statistical analysis

To analyze the clinical motor test scores, we considered whether the difference between the pre- and post-evaluation scores achieved the Minimal Detectable Change (MDC) or the Minimal Clinically Important Difference (MCID). The MDC is defined as the smallest statistically relevant change that can be detected beyond the measurement error and represents a noticeable change in ability. The MCID establishes which changes in a clinical intervention are relevant for the patient or clinician.

To analyze the piano performance, statistical analysis was conducted using Excel (Windows 2010) and the Statistical Package for the Social Sciences (SPSS version 21, SPSS inc., Chicago, Illinois, USA). Each variable was analyzed by obtaining the mean and the standard error of the mean (SEM). Execution time was obtained by calculating the average time (in milliseconds) required to play each exercise with a specific finger or combination of fingers. The mean and SEM of all the exercises performed in each session was calculated. Inter-note time was obtained by first calculating the average time (in milliseconds) taken to play each note of an exercise with a specific finger or combination of fingers. The mean and SEM of all the exercises performed in each session were calculated. Key pressure was obtained by calculating the mean of the pressure (codified as the velocity with which a key is pressed from 0 to 1) taken to play each note of an exercise with a specific finger or combination of fingers. The mean and SEM of all the exercises performed in each session was then calculated. Key pressure values were converted into a scale of 0 to 100 to conduct analysis and create the graphics.

The variables of control participants' values were obtained by calculating the mean and SEM of the performance from all subjects. SPSS was used to check if there were significant differences between controls' age. Before comparing patients' performance with controls' performance, we made sure to have a homogeneous sample of control participants by calculating the coefficient of variation (CV) of each variable in each exercise.

The mean and SEM of patients and controls' piano performance values were visually reported in graphical representations. The controls' values were reported as the baseline, and patients' values were reported individually and on average in each session. This allowed us to observe the speed and force tapping progression of patients over the whole intervention, as well as checking whether their values achieved control values performance.

Results

Demographic and clinical data

The demographic and clinical characteristics of the five patients (P01, P02, P03, P04 and P05) are presented in *Table 2*. Four female patients and one male patient (mean age 52.6 years ± 13.3; mean time since stroke 3 years and 8 months ± 36.38) participated in the study and they all consented to participate. Three patients had an ischemic stroke, and two patients had a hemorrhagic stroke (three in the right hemisphere and two in the left hemisphere). The patient P05 had a moderate level of hemiparesis, while the other patients had a mild level of impairment. All were right-handed. Only patient P01 had prior musical training (4 years of non-professional piano experience before the age of 18). Patients P02 and P03 completed the first half of the intervention in the hospital with a therapist and the second half at home alone. Patients P04 and P05 completed all the intervention at home using the updated version of the app modified from the first three participants' feedback. Patient P01 completed the first 15 sessions in the hospital and only 10 sessions at home. This patient did not complete the whole intervention due to personal reasons. *[Table 2 near here]*.

Feasibility and usability questionnaires

According to patients' feasibility feedback they overall felt competent completing the whole intervention and comfortable playing all the instruments. Using the feasibility structured interview answers, the following aspects of the eMST program were adjusted: each percussion exercise was extended to one minute as patients felt thirty seconds was too short; the MIDI-piano keys' sensitivity was increased to avoid overstraining and ensure auditory feedback as patients P01 and P02 did not hear the notes when playing with minimum force in their first two sessions; a visual cue was added in percussion exercises to facilitate performance; three games called *Piano Hero*, *Combo* and *Impro* were added to increase the number of optional activities outside of the musical learning program; the options to hear a voice message from the therapist at the beginning of each session and to record a voice message at the end of each session were added to establish a closer feeling of contact; and a ten-week intervention calendar was added so patients can check which sessions have been completed and which sessions remain.

Regarding the patients' feedback concerning technical aspects of the app, the following elements were changed to improve usability: the font size of the instructions was enlarged to a higher comfort of lecture; the scoring system was changed to a vertical score bar with stars that fills up as the exercise is being followed because patients did not understand the original system; and the option to connect speakers to the tablet was added as some patients could not clearly hear the audio instructions and piano performance.

Patients answered the usability questionnaire at the end of the intervention (see *Table 3*). The mean of patients' responses revealed that they considered the app as a useful and easy device to keep training their motor functions. More specifically, patients reported feeling confident using it during the intervention (mean = 5) and they would like to continue using it frequently (mean = 4). Patients found the app easy to use without help (mean = 4,5) and to learn how it works (mean = 3,5), considering all the functions to be well integrated (mean = 4,75). Patients provided low scores when they were asked about needing previous knowledge to use the app (mean = 2) or assistance (mean = 1,5), and whether it was unnecessarily complex (mean = 2,25) or with any awkward (mean = 1,25) or inconsistent (mean = 1,75) elements. *[Table 3 near here]*.

Clinical evaluation

The clinical motor tests scores of patients P02, P03 and P05 evaluated pre- and post-intervention are shown in *Table 4*. Patients P01 and P04 were not evaluated post-intervention due to personal constraints. *[Table 4 near here]*.

In the ARAT, CAHAI and FMA, patients P02 and P03 obtained high scores and patient P05 lower scores before the intervention. After completing the intervention, the three patients demonstrated an improvement in the three tests, reaching the MCID in the ARAT and the CAHAI. Patients P02 and P03 did not reach the MCID in the FMA due to a ceiling effect: the initial high score did not allow for a 5.2-point difference from the maximum high score. Patient P05 showed greater improvements in the three tests and reached the MCID in the FMA. In the BBT and NHPT none of the patients reached the MDC and only patient P02 showed an improvement post-intervention. Patient P05 did not complete the NHPT due to motor impairment.

Piano performance

Three variables were chosen to analyze the evaluation exercises of patients' piano performance: 1) execution time in milliseconds, 2) inter-note time in milliseconds, and 3) key-pressure from 0 to 100. Patient P01 did not complete the whole intervention and their values performance reached session 25. All the controls' piano performance obtained a

CV <40% (see *Table 5*), considering this sample sufficiently homogeneous to be used as the baseline of people without motor impairments. *[Table 5 near here]*.

Execution time

The execution time represents the tapping speed with which each piano exercise is played. The less time required by the patients to play the exercises, the quicker they are able to move their fingers, which means an improvement in fine mobility. Patients P02 and P05 required more time than other participants to complete the exercises and demonstrated a progressive improvement in *Exercise 1 (*see *Figure 2A)*. In *Exercise 2*, patient P02 demonstrated a higher performance improvement from session 4 and patient P05 remained consistent over baseline values with variability between sessions (see *Figure 2B*). Patients P01, P03 and P04 remained constant and close to baseline values over the intervention, particularly patients P01 and P04 in *Exercise 1*, and patients P03 and P04 in *Exercise 2*. Patients' average execution time values demonstrated a tendency to reach controls' performance, particularly in *Exercise 2*.

Inter-note time

The inter-note time represents the tapping speed with which each note is played in a specific exercise. The lower the time patients require to press each key, the faster they are playing the piano, signifying an improvement in fine mobility. In *Exercise 1,* patients P02 and P05 performed slower than the other participants and demonstrated a progressive improvement with a slight tendency to reach controls' performance over the intervention (see *Figure 2C*). Patients P01 and P04 played faster from the beginning and reached controls' performance at sessions 23 and 18 respectively. Patient P03 appeared to remain constant throughout the intervention with higher values than baseline and with variability between sessions. In *Exercise 2*, patients P01, P03 and P04 remained close to controls' performance over the intervention with a tendency to reach them, patient P04 being the only one who reached them in session 17 (see *Figure 2D*). Patient P02 started with the slowest performance and demonstrated the highest improvement over the first four sessions, followed by a progressive tendency to reach controls' performance. Patient P05 showed a consistent performance with variability between sessions not reaching baseline values throughout the whole intervention. Patients' average inter-note time values showed the same pattern as in execution time: they demonstrated a tendency to reach controls' performance in both exercises, particularly in *Exercise 2*. *[Figure 2 near here]*.

Pressure

The pressure applied to the keys of the MIDI-piano represents the tapping force with which the notes are played. The more pressure patients apply on the keys, the stronger their fingers are, which in turn means an improvement in fine motor functions. In both exercises, patient P01 showed an increase in force tapping in the first three sessions reaching controls' performance (see *Figure 3*). Patient P04 demonstrated high pressure values similar to controls' performance throughout the intervention. Patients P02, P03 and P05 were not close to reaching controls' performance over the intervention in both exercises. Patients P02 and P03 showed high variability between sessions and patient P05's force tapping slightly decreased throughout the intervention. Patients' average pressure values did not reach controls' performance showing a slight decrease in force tapping over the last five sessions. *[Figure 3 near here]*.

Intervention adherence and safety

The intervention adherence of each patient during the study is presented in *Table 6*. The eMST rehabilitation program was designed to be completed in 10 weeks, doing 3 self-training sessions per week. With the exception of participant P01, who did not complete the whole intervention due to personal constraints, the rest of participants completed the 30 sessions. Only patient P05 did it in 10 weeks, while the rest of participants needed one or two weeks more, doing one or two sessions over a fortnight due to Summer Holidays, Eastern Holidays or personal constraints. Regarding the time per session, the first three participants took less than one hour on average to complete each session (between 33 and 44 minutes). For this reason, we extended the time per percussion exercise. This modification was made before patients P04 and P05 started the intervention. They needed less than 1h and around 1h on average respectively to complete each session [*Table 6 near here*].

We did not observe and the participants did not report any serious or adverse safety concerns arising from completing the home-based eMST intervention at home. During the self-training sessions, in which the participants touched an electronic tablet and manipulated little percussion instruments, most of time sitting in a chair, no pain or uncomfortableness were notified.

Discussion

The present pilot study examined the feasibility of a novel eMST intervention designed to improve upper limb motor function in patients with chronic stroke. This study allowed to evaluate and improve the feasibility of the eMST program by modifying some aspects of the intervention and technical features of the eMST app according to patients' feedback. The importance of conducting pilot studies testing the feasibility and usability of novel interventions and devices should be underlined. These kind of studies provide the opportunity to check if the implementation of a novel intervention could be effective before conducting a clinical trial (52). Importantly, this study demonstrated the feasibility of the eMST program by evaluating the usability of the eMST app, the motor function gains in the affected upper limb, the intervention adherence and the safety of conducting this home-based intervention.

From the feasibility feedback regarding the eMST program and the usability questions about the eMST app, some aspects were modified. These changes increased the feasibility of the intervention and the usability of the home-based device. The app obtained usability ratings higher than 3 (and lower than 3 in the negative statements) at the end of the intervention, fulfilling the feasibility success criteria regarding the usability of the app. All patients reported the app as easy to use at home by themselves and they would recommend it and use it again. This conforms with previous research on TR programs which reported high usability and satisfaction ratings regardless of the type of therapy (42). Previous studies have also highlighted several advantages such as easier accessibility and the opportunity to conduct sessions in patients' home, which has been linked to better recovery (61). Patients overall were fully engaged in the home-based sessions. This suggests high levels of motivation possibly due to the perception of learning a new, enjoyable and socially valued leisure activity (58).

Regarding the clinical assessment, patients demonstrated a decrease in upper limb motor deficits after completing the eMST intervention. In line with previous studies, they showed clinically relevant improvements in functional movements such as grasping and pinching, which was reflected in a better performance in daily living activities (33, 53, 54). However, hand and finger dexterity improvements were not observed. Previous research in patients with chronic stroke has not found relevant clinical improvements in finger dexterity using the NHPT after completing MST programs and has been argued that motor gains cannot be observed using this test (34, 53, 55). The motor improvements were greater in patients P02 and P05 possibly due to the fact that had more severe hemiparesis and therefore a higher prospect for motor function recovery. These results indicate that the adaptation of the eMST program for home use promote the same motor improvements as the original MST program completed in the hospital (32, 42, 55-57). This suggest that MST interventions can improve motor function post stroke regardless of completing a home-based or a hospital-based intervention.

Regarding piano performance, patients overall demonstrated the ability to play faster throughout the intervention with a tendency to reach healthy controls' performance. This is in consonance with previous research applying MST for subacute and chronic stroke where patients improved in finger tapping tasks, functional movements and daily activity performance (32, 34, 53-55). In *Exercise 2*, the speed tapping improvement was greater during the first training sessions similar to previous MST studies (54, 58). This is in line with motor learning theories suggesting that a new motor skill develops more quickly at the beginning of training as the practice of a new motor task leads to initial memory acquisition and is consolidated at the end of training (59). In contrast, in *Exercise 1* time performance values tended to decrease in a progressive way, possibly because this evaluation exercise was simpler and easier to memorize from the first session. Moreover, *Exercise 2* appeared to be more sensitive to evaluate motor learning in speed tapping as patients' average values showed a higher tendency to reach controls' values than in *Exercise 1*. This may be due to the fact that patients applied more effort and concentration in *Exercise 2*. Regarding force tapping, patients overall maintained it constant and lower than controls throughout the intervention showing a slight decrease in the last week. Only one patient improved in force tapping following the typical trajectory of motor learning observed in previous studies (54, 58). These results could be due to different factors: patients felt tired at the end of the intervention; patients realized that they could do the exercises faster if they applied less force onto the keys; or patients who completed the first half of the intervention at the hospital became distracted at home over the second half of the intervention. The only patient that demonstrated force and speed tapping similar to controls over the whole intervention was possibly because of having previous piano training. Although patients applied less force to play the piano evaluation exercises, they required less time to complete them throughout the intervention. This demonstrates that eMST involves task-specific training aimed to elicit similar processes that occur in motor skill learning (60). These results can be reflected in the relevant clinical improvements observed in the functional hand movements assessed in the ARAT (grasping, gripping and pinching), which could have been promoted by the speed tapping improvement observed in the piano performance.

Regarding the intervention adherence, only one participant completed the total 30 sessions in 10 weeks, bringing to light the potential difficulties we may have in recruiting patients in a 10-week period that may overlap the Summer and Easter Holidays. Thus, we will consider organizing the recruitment timing to avoid a decrease in the adherence rate. Regarding the time needed per session, the first three participants took less than one hour on average to complete each session. After extending the percussion exercises time, patient P05 needed around 1h to complete each session, but participant P04 took half an hour possibly due to the fact they had the lowest level of hemiparesis.

The motor improvements were observed in patients with different motor deficit levels, type of stroke, affected hemisphere, and time period since stroke. This is one of the strengths of the current study as it provides the chance to examine the general effect of the eMST program on the chronic stroke population. The study also showed some limitations: the assessment was not blind, which might have biased motor outcomes; the intervention delivery form was heterogeneous between participants as not all of them completed the full eMST program at home, which might have biased expected results in a novel home-based rehabilitation program; the MIDI-piano keys' sensitivity was not increased until the third session completed by the first two participants, which could bias the piano performance results obtained from their first two sessions.

In conclusion, this pilot study demonstrates the feasibility of the eMST program for patients with chronic stroke. We tested the usability of the eMST app, the safety and adherence to the intervention, as well as examining the potential upper limb motor function improvements in patients with different type of stroke, time since stroke, age and level of hemiparesis. In addition, we had the opportunity to examine the usefulness of the piano evaluation exercises. These findings give an insight into how to manage experimental resources as well as to analyze the results in future studies using the eMST program as a telerehabilitation tool.

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Data availability statement

Anonymized data will be shared with qualified investigators on request. Data and materials can be accessed by contacting the corresponding author and in the research group webpage: https://www.brainvitge.org.

Declaration of interest statement

The authors report no conflicts of interest.

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Table 1. Piano evaluation exercises. This table provides the musical characteristics of the piano evaluation exercises daily played by the chronic stroke patients. The exercises are upward series played with all the fingers and combination of fingers. The numbers in the arrangement represent the eight notes of the C major scale (being 1 = C, 2 = D, 3 = E, 4 = F, 5 = G, 6 = A, 7 = B, and 8 = C').

Evaluation exercise	Characteristic	Arrangement
1	Individual tones	1, 2, 3, 4, 5, 6, 7, 8
2	Interval of 2 tones	1 2, 1 3, 1 4, 1 5, 1 6, 1 7, 1 8

Table 2. Demographic and clinical data. This table provides the demographic and clinical information of the five patients engaged in the eMST program for the pilot study. The level of motor impairment is the *Fugl-Meyer Assessment of Motor Recovery after Stroke* score pre-intervention.

Patient	Gender	Age	Lesioned hemisphere	Affected extremity	Type of stroke	Dominant hand	Time since stroke	Hemiparesis severity level
P01	Female	49y	Right	Left	Hemorrhagic	Right	3y 10m	64
P02	Female	33y	Left	Right	Hemorrhagic	Right	11m	61
P03	Female	51y	Right	Left	Ischemic	Right	8y 8m	59
P04	Female	65y	Left	Right	Ischemic	Right	3y 3m	66
P05	Male	65y	Right	Left	Ischemic	Right	1y 8m	41

Table 3. System Usability Scale responses. This table shows the answers of four patients to 10 statements regarding the usability of the eMST app. The questionnaire was answered with a 5-point scale (From *1: Strongly disagree* to *5: Strongly agree*) at the end of the intervention. Patients' comments are also provided in the table.

System Usability Scale					
Items	**P02**	**P03**	**P04**	**P05**	**Mean**
1) I think that I would like to use this website frequently.	5	2	5	4	4
2) I found this website unnecessarily complex.	1	1	4 ("It can be difficult depending on the patient's condition")	2	2
3) I thought this website was easy to use.	5	5	5 ("It can be difficult depending on the patient's condition")	3	4.5
4) I think that I would need assistance to be able to use this app.	1	1	2 ("I would not need assistance to be able to use the app but the tablet")	2	1.5
5) I found the various functions in this website were well integrated.	5	5	5 ("Now better than the first week due to the fact that the app has been updated")	4	4.75
6) I thought there was too much inconsistency in this website.	1	2	1	3	1.75
7) I would imagine that most people would learn to use this system very quickly.	5	3 ("I would be necessary to conduct the first session with the therapist")	3 ("It can be difficult depending on the patient's condition")	3 ("It can be difficult depending on the patient's condition")	3.5
8) I found this website very cumbersome/awkward to use.	1	1	1	2	1.25
9) I felt very confident using the system.	5	5	5	5	5
10) I needed to learn a lot of things before I could get going with this website.	1	4	1 ("I have needed to learn how the tablet works")	3	2.25

Table 4. Clinical evaluation data. This table provides the scores in all clinical motor tests test of patients P02, P03 and P05. There is no maximum value in NHPT and BBT tests. The improvement in the NHPT is negative due to the fact that conducting the task in less time means a better performance. (ARAT: *Action Research Arm Test*; FMA: *Fugl-Meyer Assessment of Motor Recovery after Stroke*; BBT: *Box and Block Test*; NHPT: *Nine Hole Pegboard Test*; CAHAI: *Chedoke Arm and Hand Activity Inventory*; AE: Affected Extremity; NAE: Non-affected extremity).

Clinical test		**ARAT**	**FMA**	**BBT - AE**	**BBT - NAE**	**NHPT - AE**	**NHPT - NAE**	**CAHAI**
Maximum value		57	66	Normative data	Normative data	Normative data	Normative data	91
MCD/MCID		5.7	5.2	5.5	5.5	32.8’	32.8’	6.3
P02	PRE	46	61	39	66	64’	17’	68
	POST	55	66	43	63	36’	19’	86
	Improvement	9	5	4	-3	-28’	2’	18
P03	PRE	51	59	40	58	41’	19’	74
	POST	57	61	42	58	39’	20’	85
	Improvement	6	2	2	0	-2’	1’	11
P05	PRE	36	41	27	53	-	20’	37
	POST	46	51	27	56	-	22’	45
	Improvement	10	10	0	3	-	2’	8

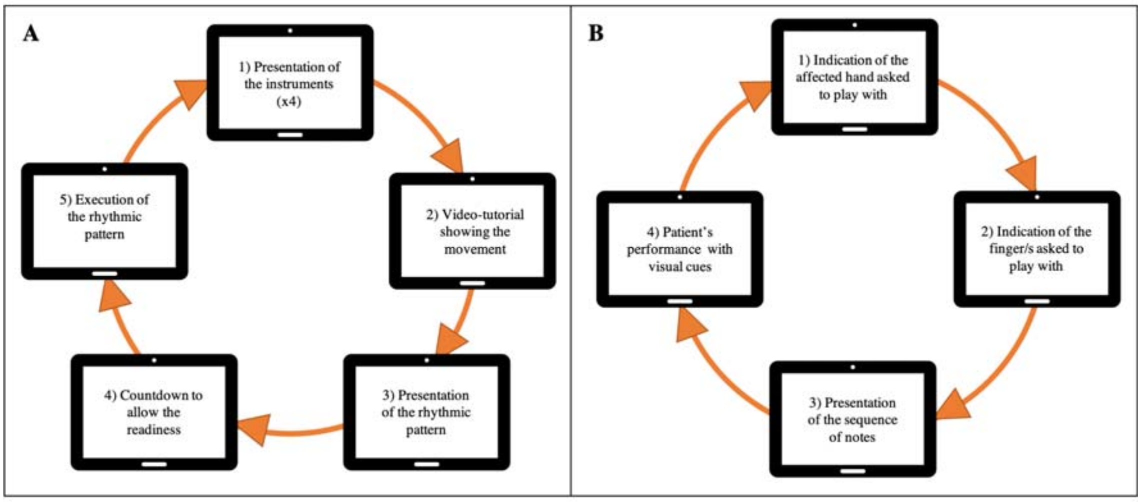
Table 5. Control participants' coefficient of variation. This table provides the Coefficient of Variation (CV) in percentage of the total duration, inter-note time and key pressure scores obtained by controls' participants in the two piano evaluation exercises.

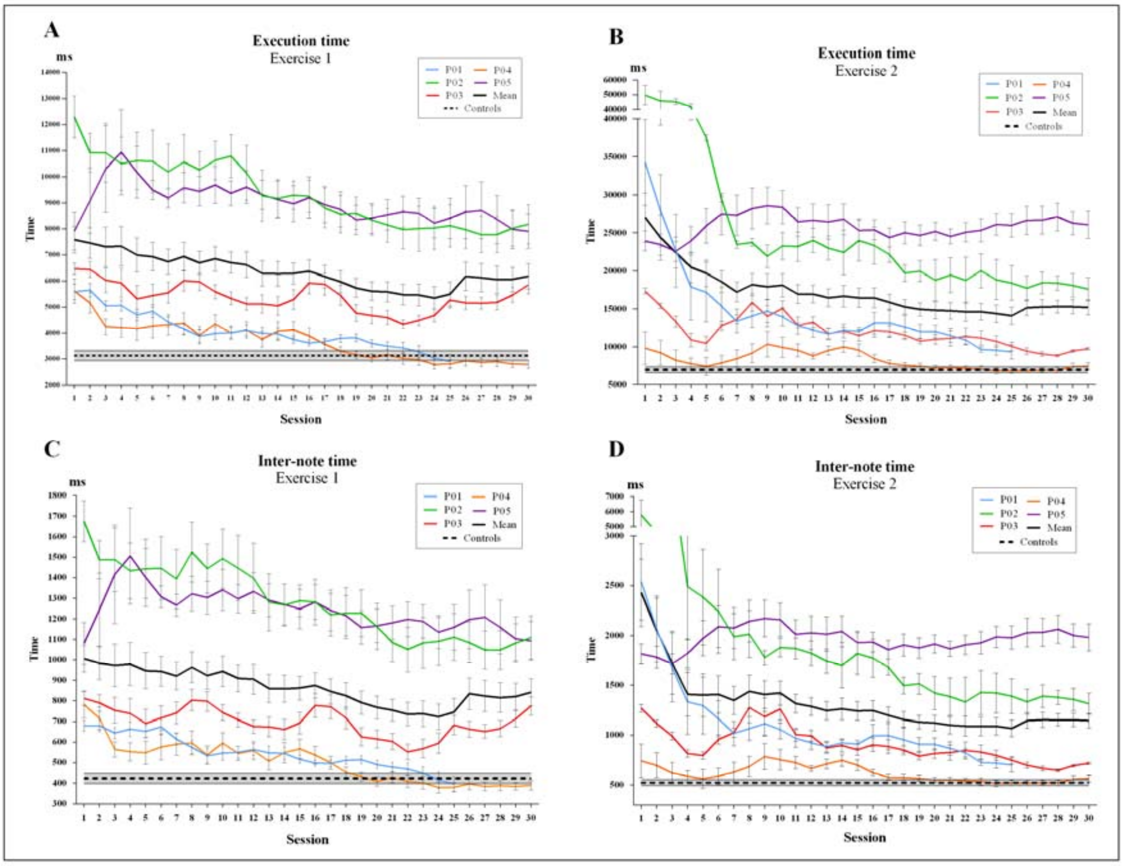
Evaluation exercise	Coefficient of Variation		
	Total duration	Inter-note time	Key pressure
1	23.7%	21.81%	9.48%
2	23.7%	23.85%	10.35%

Table 6. Participants' intervention adherence. This table provides the total number of sessions completed by each participant, the weeks they needed to complete the whole intervention, as well as the average of sessions per week and the mean and SD of the time needed to complete the sessions.

Patient	Sessions completed	Intervention duration (weeks)	Mean of sessions per week	Average session time (minutes)
P01	25	12	2'08	33±8
P02	30	11	2'73	40±7
P03	30	11	2'73	44±8
P04	30	12	2'5	37±9
P05	30	10	3	74±10

Figures 1, 2 and 3





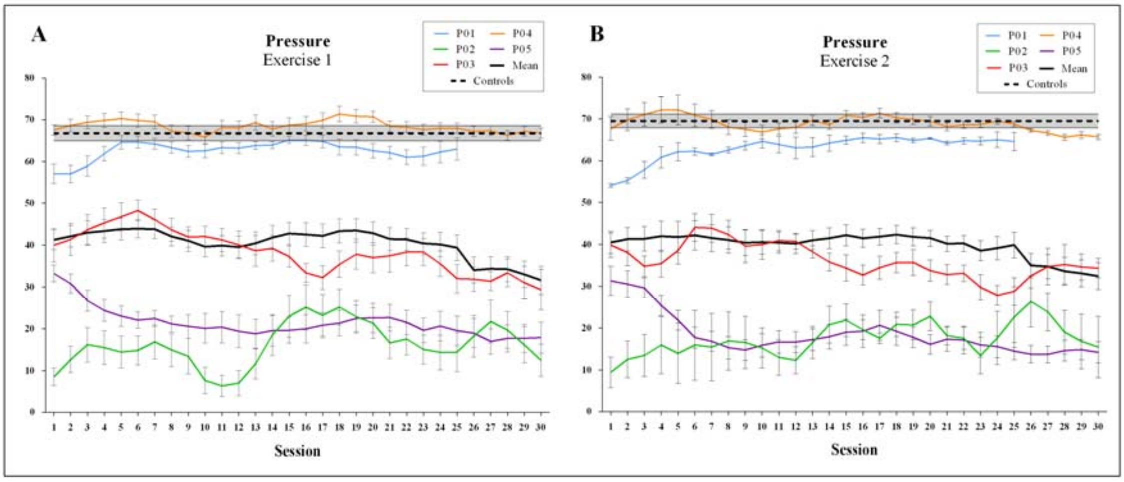


Figure 1. Exercises instruction for patients on the app. This figure shows the instructions presented on the app regarding the percussion exercises (A) and the MIDI-piano exercises (B). The sequence of the percussion instruction (A) is repeated for the four instruments required to play in each session.

Figure 2. Patients' speed tapping. This table is a graphical representation of patients P01, P02, P03, P04 and P05's performance while playing the piano evaluation *Exercise 1* (A and C) and *Exercise 2* (B and D) over 30 sessions (25 in the case of P01) regarding the two variables related to speed tapping: execution time (A and B) and inter-note time (C and D). The black line represents the patients' average performance. The dotted line represents the mean of controls' execution time values, and the grey bar represents the SEM of controls' execution time values.

Figure 3. Patients' force tapping. This table is a graphical representation of patients P01, P02, P03, P04 and P05's performance while playing the piano evaluation Exercises *1* (A) and *Exercise 2* (B) over 30 sessions (25 in the case of P01) regarding the variable related to force tapping: pressure. The black line represents the patients' average performance. The dotted line represents the mean of controls' execution time values, and the grey bar represents the SEM of controls' execution time values.