

Development and Evaluation of a Novel Music-based Therapeutic Device for Upper Extremity Movement Training

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Abstract

Background

Restoration of upper limb motor function and patient functional independence are crucial treatment targets for neurologic recovery. Growing evidence indicates that music-based intervention is a promising therapeutic approach for the restoration of upper extremity functional abilities in neurologic conditions. In this context, music technology may be particularly useful to increase the availability and accessibility of music-based therapy and assist therapists in the implementation and assessment of targeted therapeutic goals. In the present study, we describe and evaluate a novel music-based therapeutic device (SONATA) for upper limb extremity movement training.

Methods

The device consists of a graphical user interface generated by a single-board computer displayed on a 32" touchscreen with build-in sound speakers controlled wirelessly by a computer tablet. The system includes two operational modes that allow users to play musical melodies on a virtual keyboard or draw figures/shapes whereby every action input results in controllable sensory feedback. Four functional tests were performed with 21 healthy individuals (12 males, age 26.4 ± 3.5 years) to evaluate the device's operational modes and main features, such as presenting sequences of audiovisual stimuli at a pre-defined order (Tasks 1–3), displaying different shapes (Task 4), and collecting response and movement data (e.g., reaction time, correct/incorrect responses, and timing data).

Results

The results indicate feasibility and ease of use of the device, as shown by the participants' performance accuracy in all tasks. The findings also demonstrate the reliability of the data acquired automatically by the system as we replicated the results of previous research showing a decrease in reaction time in sequences repeatedly presented in relation to random sequences, and that sequence length, rate and complexity affect accuracy of newly learned action sequences.

Conclusions

This device is a feasible tool for upper limb extremity movement training and opens new avenues for the systematic evaluation of the benefits of music technologies in clinical research.

Background

Effective use of the arm and hand to reach, grasp, release, and manipulate objects is often compromised in individuals with neurologic disorders such as cerebral palsy [1], post-stroke [2, 3], Parkinson's Disease

[4, 5], among others. Impairments of upper extremity function include reduced muscle power, sensory loss, increased muscle spasticity, and lack of motor control [1, 6–8], resulting in significant long-term functional deficits with relevant impact on patients' activities of daily living, independence, and quality of life [9–12]. Therefore, improving upper limb functional abilities and promoting functional independence are crucial treatment targets for neurologic recovery.

Functional restoration of the upper extremity is thought to be achieved through a combination of neurophysiological and learning-dependent processes that involve targeted training to restore, substitute, and compensate the weakened functions [13, 14]. Frequently reported neurorehabilitation approaches for upper limb movement in cerebral palsy [15, 16], post-stroke [13, 17] and Parkinson's Disease [18, 19] include standard treatment methods such as general physiotherapy (i.e., muscle strengthening and stretching), constraint-induced movement therapy and bimanual training, as well as technology-based approaches (i.e., virtual reality, games, and robot-assisted training) [20–26], and music-based interventions [27–29].

There is growing evidence that music-based interventions are a promising therapeutic approach for the restoration of upper extremity functional abilities in neurologic conditions including stroke [30, 31], cerebral palsy [32, 33], and Parkinson's Disease [28, 34]. For instance, there is extensive research on the effectiveness of Therapeutic Instrumental Music Performance in rehabilitating arm paresis after stroke through musical instrument playing [35–44]. Similarly, active musical instrument playing (i.e., piano) also seems to improve manual dexterity and finger and hand motor function in individuals with cerebral palsy [33, 45–47]. Furthermore, consistent evidence indicates that interventions using rhythmic auditory cues or rhythmically-enhanced music [34, 48, 49] are effective to increase muscle activation symmetry [50], improve range of motion and isometric strength [51, 52], enhance spatiotemporal motor control [53], and decrease compensatory reaching movements [50]. Importantly, the improvement in motor skills observed with active music-based therapy is reported to be specifically caused by music rather than by motor training alone, since post-stroke patients who underwent a 4-week intervention with muted musical instruments showed less improvement than patients in the audible musical instrument training [38].

Music-based movement rehabilitation for upper limb training is particularly interesting since playing a musical instrument provides real-time multisensory information that enhances online motor error-correction mechanisms and supplements possible perceptual deficits [54–56]. Research has also shown that the engagement of multisensory and motor networks during active music playing promotes neuroplastic changes in functional networks and structural components of the brain, which are crucial neurophysiological processes for neurologic recovery [39, 57–61]. Moreover, there is robust evidence that the use of metronome or beat-enhanced music is important to support movement training as the continuous-time reference provided by the rhythmic cues allow for movement anticipation and motor preparation, bypassing the movement timing dysfunction through the activation of alternate or spared neural pathways [49, 62, 63]. Finally, emotional-motivational aspects of music-making also play a significant role in the rehabilitating effects of music-based intervention through music-induced changes

in mood, arousal, and motivation [27, 64], with potential effects on perceived physical endurance and fatigue [30, 65].

Recently, studies have acknowledged the relevance of music technology to increase the availability and accessibility of music-based therapy for patients with neurological disorders in different settings, including hospitals, communities, and home environment [29, 66–68]. For example, the use of programmable devices can help patients to exercise independently in addition to scheduled caregiver-guided sessions, thus increasing treatment intensity [68]. Technology may also assist therapists in the implementation of individual therapeutic goals and provide immediate assessment of measurable changes with objective outcome measures (e.g., total movement time, movement variability, force, inter-response interval). Additionally, digital music and sound devices can provide enhanced auditory feedback to kinematic movement components such as velocity and acceleration, range of motion, joint angles, spatial and temporal limb trajectories, even in stages of limited physical movement capability [67, 69].

With that in mind, a novel music-based therapeutic device for upper extremity movement training was developed to improve upper extremity motor function, to increase independent patient engagement, to enhance treatment quality, intensity, and compliance, and to assist therapists during treatment implementation and assessment. Therefore, the objective of this study is to describe a music-based therapeutic device called SONATA and to evaluate the feasibility of the system's functioning for upper extremity movement training. For this purpose, four clinically relevant functional tests were implemented in a convenience sample of healthy individuals to examine the system's key mode (Tasks 1–3) and drawing mode (Task 4) and to assess the reliability of some of the device's main features such as the presentation of sequences of audiovisual stimuli at a pre-defined order and data acquisition of response and movement data (e.g., reaction time, correct/incorrect responses, inter-response interval).

Methods

Device Hardware and Software

The SONATA device consists of a custom-made graphical user interface generated by a single-board computer (Raspberry Pi 2 B with HiFiBerry) displayed on a 32" touchscreen (iiyama ProLite T3234MSC-B3X; visible screen size: 698.4 × 392.8 mm; resolution: 1920 × 1080 pixels, pixel spacing: 0.364 × 0.364 mm) with build-in sound speakers and controlled wirelessly by a computer tablet (Acer One 10) (Fig. 1). The hardware and software of the system have been designed to minimize any latency between user input and sound output.

Device Design, Input And Settings

The touchscreen user interface is programmed through a controller tablet pc to individualize the therapist's and the patient's work surfaces. This allows for the therapist to graphically and acoustically program the desired exercises using the controller tablet pc, while the tasks are performed by the patient

using the touchscreen interface under the guidance of the therapist or independently. The number and the order of the training exercises can be designed and saved by the therapist in the device's memory prior to a training session. The graphical interface displayed on the controller tablet allows the therapist to choose between two operational modes (keyboard and drawing) and displays two distinct functions: Input and Settings (Figs. 2 and 3).

The Keys Mode allows the user/patient to play sound sequences on a virtual keyboard by pressing different keys represented by squares displayed on the device's touchscreen. Each keypress produces a feedback sound that corresponds to a pitch. The default input window presents a 4×8 key matrix (4 rows, 8 keys per row) and each key can be tuned in ascending semitones (from left to right) or in diatonic scales either as a single pitch or as a triadic major or minor chord. To accommodate for less precise reaching motion, the key sizes can be increased and displayed in a 2×4 key matrix. In the input function, the therapist can program and save up to 9 sound sequences by pressing the 'record' button and then playing/pressing the sequence of keys in the required order (Fig. 2). Additionally, it is possible to repeat the sequence of tones using the loop function and set the metronome tempo (in BPM) to which the participant will time their movements.

The settings function in the Keys Mode (Fig. 3) provides additional setup options where the therapist is able to select, for instance, the volume and the instrumental timbre of the feedback sounds (e.g., piano, organ, violin, guitar, trumpet, and saxophone). The sustain function determines the duration (in seconds) that the sound remains present between key presses, and the marker function enables/disables the color-highlighting function of the visual display where each key of the sequence changes color as it is presented. During the exercise, the predefined sequence of keys is displayed to the patient by turning blue in a cumulative order and simultaneously presenting the corresponding pitch. After the sequence is introduced, the patient then reproduces the sequence of keys in the correct order and synchrony with the metronome tempo. The device also includes a function where the therapist can determine a temporal window around the metronome tempo in which the patient is required to press the keys. With this function, if the keypresses occur outside of the predefined temporal interval, no auditory feedback is provided, thus encouraging the patient to maintain temporal accuracy.

In the Drawing Mode, the spatial accuracy of continuous motions is trained via sonification. The therapist can program up to 9 distinct figures or shapes that are subsequently traced by the patient using his/her finger. The default input window in the drawing mode presents an empty field into which the therapist can draw the figure/shape by touching the screen and moving the finger in the required direction (Fig. 2). Along with the movement of the finger on the screen, a continuous sinusoidal tone is presented whereby the pitch is determined by the position of the finger on the screen, with lower tones presented on the lower quadrants and higher tones on the top quadrants of the screen in ascending order from left to right and from bottom to top. Additionally, a visual guide is displayed during the drawing where the yellow line serves as a template indicating the movement trajectory to be performed and the blue frame sets the interval in pixels in which the patient has to move the finger on the screen to train spatial accuracy. During the exercise, the figure is first displayed to the patient at the same velocity and trajectory that were

recorded by the therapist, and then the patient reproduces the drawing at their preferred tempo. During the drawing, the patient's finger movement also produces a sinusoidal feedback sound that changes in pitch depending on the finger's position on the screen. It is also possible to define an area of spatial accuracy around the figure lines whereby no sound feedback is provided when the finger trajectory is outside of the predefined area.

Data Output

Every task performed on the device automatically captures relevant movement data that can be further analyzed to evaluate the patients' performance on each task from session to session, thus assisting the therapist in assessing measurable changes in upper limb function throughout the training. The recorded data are stored as ASCII files and include general information about the session (date, time, therapist), patient (name, ID code) and the task (task mode, metronome tempo (BPM), inter-stimulus interval (ms), key numbers of the recorded sequence (1 to 32, from bottom left to top right), and the temporal interval between keypresses of the recorded sequence (ms).

The output files also contain timing and location information of each patient's input. The Keys Mode includes analyzable data such as expected sequence key and patient response key (from 1 to 32), inter-stimulus interval, inter-response interval, and synchronization error [70, 71]. The output data provided in the Drawing Mode includes location information such as the x- and y-coordinates of the patient input (in pixels, 0 to 1880 and 0 to 1040 respectively), x- and y-coordinates of the nearest target section, and the distance between patient input and the nearest target section. From the data of the Drawing Mode, the speed of the hand/finger movement can also be derived providing a velocity profile of the drawing movement.

Evaluation Procedure

Participants

Functional tests were conducted with 21 healthy individuals (12 males, 8 females) recruited at the Faculty of Psychology and Movement Science at the Universität Hamburg/Germany. Participants were on average 26.4 years old ($SD = 3.5$, range 21–36 years), 3 of them indicated a preference for the left hand and 18 for the right hand. All participants reported normal hearing, normal or corrected to normal visual acuity, and had no ongoing musculoskeletal injuries that could influence normal upper limb movement.

General Procedures

Participants were seated in a regular chair in a quiet test room with the SONATA device placed on a table positioned at a comfortable distance in front of them at the wrist level (Fig. 4). Stimuli presentation and data collection were implemented with the SONATA device running a built-in custom-made software.

Before each task, participants received written instructions and were allowed to practice the tasks. With breaks, the session took approximately 50 minutes to be completed.

Tasks

Task 1: Serial Reaction Time

The Serial Reaction Time (SRT) task is a well-known paradigm used to evaluate motor sequence learning whereby participants are required to respond as rapidly as possible to targets (auditory and/or visual stimulus) that are presented either in a repeating order (sequence blocks) or in random order (random blocks) [72–75]. Findings of studies using the SRT task consistently show a decrease in reaction time in the sequence blocks in relation to the blocks where targets are presented in random order, indicating an effect of implicit motor sequence learning [72–75]. Given the robustness of the SRT paradigm, this task was implemented to examine some of the device's main features, such as the presentation of sequences of stimulus at a pre-defined order and the data acquisition of response information including response accuracy and reaction time.

In the present task, the stimuli consisted of visual targets (squares representing different pitch) displayed on a horizontal array comprised of 32 locations presented on the screen (Fig. 1). The visual targets were a light grey color. During each experimental trial, one target at a time was presented by turning blue while the corresponding auditory stimulus (piano tone of 1000 ms duration) was simultaneously presented. The target remained on the screen until the correct response was made. The participant's task was to reach the preferred arm and press the button corresponding to the target as fast and as accurately as possible. Stimuli were presented at a fixed 1-second interval and were divided into separate trials. In the random (R) trials, sequences of stimuli followed an unpredicted order. The random sequences were generated using a random number generator whereby each of the keys corresponded to a number from 1 to 32, starting from the top left (D1) to bottom right (A8). In the sequence trial (S), the same sequence of 12 tones was repeated throughout the task. In total, the task consisted of 8 trials: 4 random trials and 4 repetitions of the sequence trial, following a standard block design (RSRSSRRS).

Task 2: Unimanual sensorimotor synchronization task

The ability to learn new action sequences is known to be affected by task parameters such as sequence length, rate, and complexity [76, 77], as well as by individual differences in working memory capacity [78]. It has been well-documented that this learning ability is significantly impaired in aging [79–81], stroke [82, 83], and neurologic disorders [84]. In standard Music-support Therapy protocols, for instance, electronic keyboard and/or drum pads are used to exercise fine and gross movements whereby patients may start playing simple sequences that vary in the number of tones and the velocity, order, and limb patients are required to play, which progressively increase in difficulty [35]. Clinical studies indicate that motor improvements can be observed during the first training sessions with observable changes in movement velocity, key pressure, and note accuracy, with a generalization of motor gains to functional tasks and activities of daily living [30]. Therefore, the following tasks (unimanual and bimanual sensorimotor

synchronization) were implemented to test the feasibility of the device's Key Mode and the reliability of the data automatically acquired by the system in tasks that are often implemented in motor rehabilitation therapy.

This task evaluated the Keys Mode of the device, which allows the presentation of pre-defined sequences of melodies that are reproduced by the user by pressing different keys represented by squares displayed on the device's screen. For that, participants were presented with 8 distinct pre-defined melodies composed by 6 to 9 tones. Light grey squares representing 32 distinct pitches were displayed on the SONATA screen. During each trial, one note of the melody at the time was presented on the screen by turning blue while the corresponding auditory stimulus (piano tone) was simultaneously presented and remained on the screen cumulatively. Melodies were designed to follow different motion patterns on the screen and differed in relation to sequence length (6–9 tones) and inter-stimulus interval (slow: 66 BPM/910 ms; fast: 80 BPM/750 ms). Participants were instructed to memorize the order of each note of the melody and then reproduce the sequence in the correct order and in synchrony with the metronome using their preferred hand. Each melody was presented only once (total of 8 trials).

Task 3: Bimanual sensorimotor synchronization task

Similar to Task 2, a set of 9 pre-defined melodies composed by 7 notes was presented. During each trial, one note of the melody at the time was presented on the screen by turning blue while the corresponding auditory stimulus was simultaneously displayed. Each note of the melody was presented at a fixed tempo (BPM 80/750 ms). The participants' task was to memorize the order of each note of the melody and reproduce the sequence in the correct order and in synchrony with the metronome. Additionally, participants were instructed to press the target notes appearing on the left side of the screen with the left hand, whereas notes appearing on the right side had to be played with the right hand. Each melody was only presented once, totaling 9 trials.

Task 4: Finger tracking task

Hand and finger function is often impaired in neurologic disorders such as cerebral palsy [85, 86], stroke [87], and Parkinson's Disease [88, 89], with significant impact on tasks that require fine motor control including drawing and finger tracking [90–94]. Movement training to enhance hypometria, bradykinesia, and weakness are important treatment targets for neurologic recovery [87, 91, 92]. Training of finger movements involving tracking a target on a computer screen with reciprocal extension and flexion of movement of the index finger has been previously applied in motor rehabilitation, with results suggesting significant improvements in tracking accuracy with transfer of gains to grasp and release function [91].

This functional task was implemented to assess features of the Drawing Mode of the device including movement sonification, the presentation of different shapes, as well as the acquisition of movement data relating to accuracy and time for completion.

In this task, participants were instructed to follow two different figures displayed on the screen. One of the figures consisted of a sine wave shape (92 cm length) while the second figure was a triangle wave shape

(109 cm length) that was displayed horizontally throughout the entire screen. Participants' task was to follow the shape displayed on the screen with the index finger of their preferred hand moving from left to right at their preferred rate, repeating the task 5 times per trial. In some trials, the movement of the finger on the screen generated auditory feedback (sinusoidal tones) that changed in frequency as the finger moved upward (higher frequency) or downward (lower frequency), whereas no auditory feedback was presented in half of the trials. Figures were presented in separate blocks with counterbalanced order. Each block consisted of 8 trials; 4 trials with auditory feedback and 4 trials without auditory feedback, totaling 16 trials.

Data Analysis

In Task 1, the main variable of interest was the mean reaction times ($PAT_TIME - TICK_TIME$) for each condition (random and sequence trials). Absolute reaction time was evaluated across conditions with a univariate analysis of variance.

In task 2, we were interested in whether the number of errors (i.e. pressing the wrong note) would differ in relation to the sequence length (6 to 9 tones) and rate (slow and fast). To obtain the information regarding accuracy, we compared the output data presented in SEQ_KEY and PAT_KEY which indicated, respectively, the number corresponding to the note presented and the participant's actual response and converted the value in percentage. A two-way analysis of variance was performed with the percentage of correct responses as the dependent variable and sequence length (4) and rate (2) as factors. Additionally, we assessed whether participants were able to synchronize their movements with the metronome, using the mean and standard deviation of the inter-response interval (IRI) output variable.

In Task 3, participants performed the task bimanually, receiving instructions to press the target notes displayed on the left side of the screen with the left hand and the notes displayed on the right side with the right hand. We were interested in whether performing the task bimanually would affect accuracy (i.e. number of errors). The percentage of correct responses was obtained by comparing the output data presented in SEQ_KEY and PAT_KEY, while data on lateralization errors were recorded manually by the experimenter. Descriptive statistics are presented. Additionally, we also assessed whether participants were able to perform the task following the tempo set by the metronome (mean/standard deviation of IRI).

In the finger tracking task (Task 4), the variables of interest were the time needed to complete each trial and drawing accuracy. The information regarding time was obtained by summing the data provided in the TIME_DIFF output, which corresponds to the time difference between two points on the screen in milliseconds (screen resolution 1920×1080 pixels). Drawing accuracy is presented in the DIST output variable, which computes the distance between the template figure (SEQ_X and SEQ_Y coordinates in pixels) and the participant's drawing (PAT_X and PAT_Y coordinates). We were interested in whether the time for completion and drawing accuracy would be affected by the shape of the figure and the availability of auditory feedback generated by the movement of the finger on the screen. A multivariate analysis of variance was performed with time (milliseconds) and drawing accuracy (pixels) as the

dependent variable and auditory feedback (with and without) and figure shape (sine wave or triangle wave) as factors.

For all statistical comparisons, the significance level was set to 5% ($p < .05$). Statistical analysis was performed using SPSS 24.0 (SPSS Inc., Chicago, IL, USA).

Results

Task 1: Serial Reaction Time Task

Participants performed the task with an average of 100% accuracy ($SD = 1.7\%$), demonstrating that they were able to reach the correct target position in both conditions (random and sequential). The analysis of the mean absolute reaction time indicated that participants were significantly faster to respond in the sequential order ($M = 494$ ms, $SD = 40$ ms) than in the random order trials ($M = 510$ ms, $SD = 55$ ms; $p = .03$). These results concur with previous studies showing a decrease in reaction time during the sequence trials in relation to the random trials, which is indicative of implicit motor sequence learning [72–75].

Task 2: Unimanual Sensorimotor Synchronization Task

In this task, we were interested in whether accuracy would be affected by sequence length and presentation rate. Overall, participants performed the task with an average of 96% accuracy ($SD = 10\%$). Nonetheless, the analysis indicated that there were significant main effects of sequence length ($F(3,140) = 5.896$, $p = .001$) and rate ($F(1,140) = 11.036$, $p = .001$) on the percentage of correct responses, but there were no significant interaction between factors ($p = .607$). Further comparisons with Bonferroni corrections indicated that sequences with 9 tones had significantly more errors than sequences with fewer tones ($p < .05$), and that sequences presented and performed at a faster rate had more errors than sequences at a slower tempo ($p = .02$). Analysis of the IRI showed that participants were able to time their movements according to the metronome tempo, as the average IRI during the slow sequences was 897 ms ($SD = 153$ ms) and during the fast sequences the average IRI was 740 ms ($SD = 77$ ms).

Task 3: Bimanual Sensorimotor Synchronization Task

Overall, the task was performed with an average accuracy of 85% ($SD = 20\%$), suggesting that performing the melodic sequences with both hands resulted in an increased number of errors (i.e. pressing the wrong note). When considering lateralization errors, the average accuracy was 99% ($SD = 2.8\%$), demonstrating that participants were able to perform the task using the correctly assigned hand. Finally, the analysis indicated that participants performed the task with an average of 791 ms inter-stimulus interval ($SD = 223$ ms), thus significantly slower ($t(166) = 2.394$, $p = .018$) than the tempo set by the metronome (BPM 80/750 ms).

Task 4: Finger Tracking Task

In task 4, participants had to track with their index finger distinct shapes following a template displayed on the screen. We were interested in whether the time for completion and drawing accuracy would be affected by the shape of the figure and the availability of auditory feedback generated by the finger movement on the screen. Statistical analysis indicated that there were no significant interactions or main effects of figure shape or auditory feedback condition on time and drawing accuracy. Drawing accuracy, as measured with the mean distance between the participants' finger trace and the figure template (in pixels), did not differ significantly in the sine wave shape ($M = 22.5$, $SD = 53$) and triangle wave ($M = 22.3$, $SD = 60$, $p = .98$). When considering the effect of the availability of auditory feedback, mean drawing accuracy was not significantly different ($p = .12$) in the auditory feedback condition ($M = 29.25$ pixels, $SE = 6.2$) and with no feedback ($M = 15.58$ pixels, $SE = 6.2$). Time for completion also did not differ significantly between sine wave ($M = 46659$ ms, $SD = 136274$ ms) and triangle wave ($M = 68973$ ms, $SD = 342537$ ms, $p = .58$), and between trials with auditory feedback ($M = 84643$ ms, $SE = 28432$ ms) and without auditory feedback ($M = 30989$ ms, $SE = 28432$ ms, $p = .18$).

Discussion

In this study, we describe a novel music-based therapeutic device for upper extremity movement training called SONATA and evaluate the system's functioning in a convenience sample of healthy individuals. Four clinically relevant functional tests based on well-known research paradigms were implemented to test the device's two operational modes (keyboard and drawing) and main features, including the presentation of pre-defined sequences of audiovisual stimuli and shapes, and collecting response and movement data.

Overall, the results of the functional tests indicated the feasibility and ease of use of the device with healthy individuals as shown by the participants' performance accuracy in all tasks. Our findings also demonstrated the reliability of the data acquired automatically by the system as we replicated the results of previous research. In Task 1, results indicated a decrease in reaction time in trials where targets are presented in a repeating order compared to random order, as previously reported [72–75]. The results of Tasks 2 and 3 concur with the notion that sequence length, rate, and complexity [76, 77] significantly affect the accuracy of newly learned action sequences, as findings indicated that sequences with 9 tones had significantly more errors than sequences with fewer tones; that sequences presented and performed at a faster tempo had more errors than slower sequences; and that performing melodic sequences bimanually resulted in an increased number of errors. Task 4 revealed that healthy participants' were equally accurate in tracking a sine- or triangle-wave shape in different movement sonification conditions.

This study also highlights the potential utility of the device in therapy. All tasks administered here required the presentation of pre-defined sequences of audiovisual stimuli or shapes and were designed to include different sequence lengths, presentation rates, task complexities, changes in the availability of real-time auditory feedback, and movement sonification, as well as capturing distinct response and

movement data. These are all aspects carefully considered in the implementation of individual therapeutic goals, thus indicating that the device may assist therapists during treatment implementation and assessment of targeted therapeutic goals. The functional tests also exemplify the types of tasks that can be implemented with the device in motor and cognitive rehabilitation to train gross and fine motor functions, improve spatiotemporal motor control, increase range of motion, as well as to enhance motor sequence learning and train cognitive functions such as working memory and attention. With the device, we were able to adapt tasks often used, for instance, in music-based intervention protocols that utilize an electronic keyboard and/or drum pads are used to exercise fine and gross movements [30, 35] as well as finger movement training tasks that involve tracking a target on a computer screen [91].

Studies have consistently demonstrated that active music playing is effective to train upper extremity movement [35–44] due to crucial elements, such as the display of real-time multisensory information [54–56] and the use of metronome or beat-enhanced music to support movement training [49, 62, 63], which promote neuroplasticity [39, 57–61] and relevant changes in mood, arousal, and motivation [27, 64]. In addition to all the elements involved in active music playing with traditional acoustic musical instruments, there are possible advantages of the use of technology and devices such as the SONATA in music-based therapy, including the availability of features that allow for better control and documentation of the training exercises implemented in each session. Furthermore, this device captures and records movement data (such as total movement time, movement variability) from a variety of tasks, providing an objective depiction of the patient's motor function profile, thereby assisting in the implementation of individual therapeutic goals. Finally, the ability to easily access such devices in various environments, such as in the home or at a hospital, allow for self-implemented training, which may contribute to increased training intensity and rate of recovery within upper limb rehabilitation and may, in turn, empower and encourage the patient to continue engaging in active exercises.

Beyond representing a new and effective methodology for the analysis of individual treatment goals and patient progress, the implementation of music technologies within the daily practice in neurorehabilitation could be paramount to transform the therapeutic process [67]. In the past years, researchers have acknowledged the relevance of music technology to open the possibility of people without music training to engage in active music playing, to facilitate the access to music-based therapy in different settings, and to increase motivation and client participation, while offering professionals the opportunity to deploy more resources to meet the patient's treatment needs [95]. Nonetheless, systematic research on the benefits of music technologies in clinical research is still sparse. Thus, studies on the use of the SONATA device with clinical populations are in place to further examine the feasibility, ease of use of the device, and the reliability of the data acquired by the system in neurologic patients.

A potential limitation of this study was that the number of participants was restricted to twenty-one highly educated, young, and healthy subjects. Given the intention to use this device for rehabilitation training of upper limb extremity movement, the results of this study regarding ease of use may not apply in a patient population. Further research on user experience evaluation from patients and professionals are also needed to further examine the feasibility of the device in a therapeutic setting. Current technical

limitations of the device refer to its memory capacity, which allows a maximum of 9 sequences per task, and the need to utilize additional motion sensors to detect movement trajectory beyond the device itself, hence why data on lateralization errors in Task 3 were recorded manually by the experimenter.

Conclusions

A novel music-based therapeutic device for upper extremity movement training was presented. Four well-known tasks were implemented to test the feasibility, ease of use, and reliability of the movement and response data acquired by the system. Overall, the results of the tasks with a sample of healthy individuals indicate the feasibility and reliability of the device as a tool for upper extremity movement training. These findings open new avenues for further clinical investigation into the implementation of music technologies in neurorehabilitation to improve upper extremity motor function, to increase independent patient engagement, to enhance treatment quality, intensity, and compliance, and to assist therapists during treatment implementation and assessment.

Declarations

Ethics approval and consent to participate

The experimental procedures conformed with the Declaration of Helsinki and were approved by the Local Ethics Committee of the Faculty of Psychology and Movement Science of the Universität Hamburg. All participants were fully informed about the nature of the study and provided written informed consent to participate.

Consent for publication

Written informed consent for publication was obtained from the participants involved in the study.

Availability of data and materials

The datasets generated and/or used during the current study are not publicly available but are available from the corresponding author on reasonable request.

Competing interests

NS and TBJ declare that they have no competing interests. RP and SS are engineers at BeSB GmbH Berlin and MT has been a consultant for BeSB GmbH Berlin. The SONATA device developed and tested in this study was built in collaboration between BeSB and MT, and there is potential for commercialization.

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Author's contributions

Conceptualization: MT. Methodology: NS, TBJ, RP, SS, MT. Data acquisition, analysis: NS, TBJ. Drafting of manuscript: NS, TBJ, VV, MT. Critical revision: SS, MT. All authors read and approved the final manuscript.

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Figures



Figure 1

Device's touchscreen, graphic userinterface, and controller tablet.



Figure 2

User interface input function for the keys mode (left panel) and drawing mode (right panel).

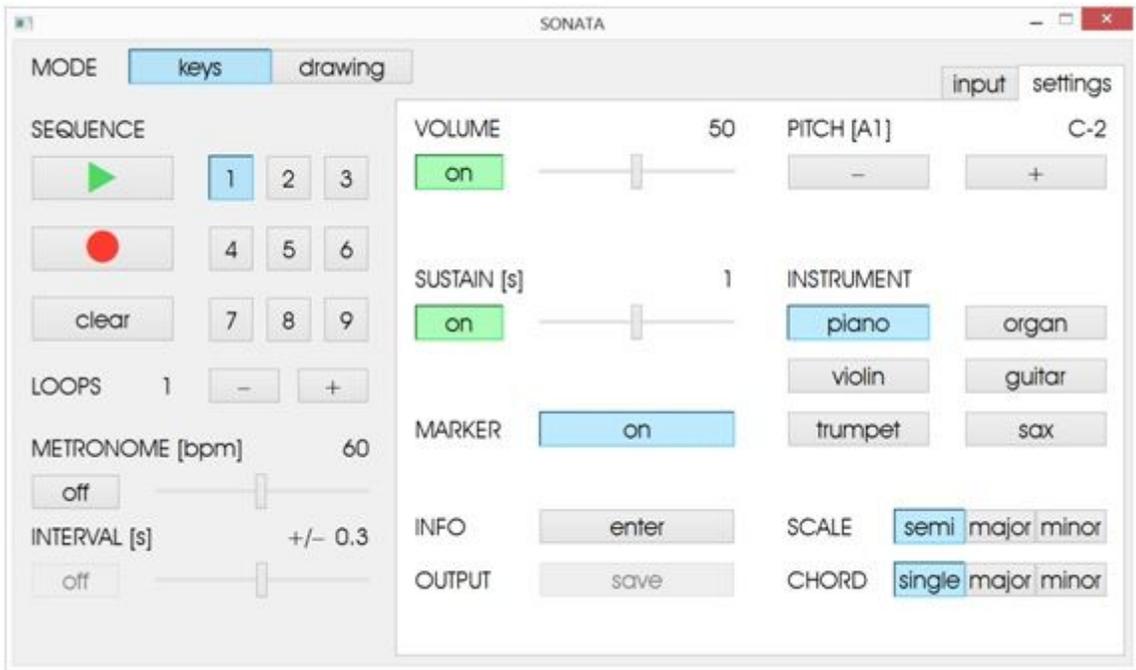


Figure 3

Settings function for the keys mode.



Figure 4

Device in use during the evaluation procedures.