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Design and development of a sensored glove for home-based rehabilitation

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A R T I C L E I N F O

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A B S T R A C T

Study Design: Descriptive.
Introduction: Rehabilitation programs that focus on motor recovery of the upper limb require long-term commitment from the clinicians/therapists, require one-to-one caring, and are usually labor-intensive.
Purpose of the Study: To contribute to this area, we have developed a sensored hand glove integrated with a computer game (Flappy Bird) to engage patients playing a game where the subject's single/multiple fingers are involved, representing fine motor skill occupational therapeutic exercises.
Methods: We described the sensored rehab glove, its hardware design, electrical and electronic design and instrumentation, software design, and pilot testing results.
Results: Experimental results supported that the developed rehab glove system can be effectively used to engage a patient playing a computer game (or a mobile phone game) that can record the data (ie, game score, finger flexion/extension angle, time spent in a therapeutic session, etc.) and put it in a format that could be easily read by a therapist or displayed to the therapists/patients in different graph formats.
Conclusions: We introduced a sensored rehab glove for home-based therapy. The exercise training using the glove is repetitious, functional, and easy to follow and comply with.

Introduction

Stroke is one of the leading causes of long-term disability. A primary concern for stroke survivors is reduced mobility. In fact, more than 50% of those who are aged 65 years and older and have survived a stroke are left with impaired mobility.[1] According to the World Health Organization, stroke affects more than 15 million people worldwide each year.[2] Among these, 85% of stroke survivors will incur arm impairment, and 40% will be chronically impaired or permanently disabled.[3] However, stroke is only one of many causes of physical disability. A loss or decrease in motor function may result from spinal cord injuries, cerebral palsy, motor neuron disease, traumatic brain injuries, Parkinson's disease, sports injury, etc. It is estimated, more than 3 million people in the USA have a disability in their hands and/or forearms, including paralyzations, orthopedic impairments, either congenital or injury related.[4] Hand injuries count for 1/3 of all injuries at work, 1/3 of chronic injuries, 1/4 of lost working time, 1/5 of permanent disability.[5] This results in a burden on their families, communities, and the country as well. Approximately 50 million family caregivers provide 37 billion hours of care worth more than an estimated $470 billion annually to their family and other loved ones.[6] The total estimated economic value of uncompensated care provided by family caregivers surpassed total Medicaid spending ($449 billion) and nearly equaled the annual sales ($469 billion) of the four largest U.S. tech companies combined (Apple, Hewlett–Packard, IBM, and Microsoft).[6] These numbers will continue to rise as the population continues to age.

Biomedical technologies that augment/restore an individual's upper extremity function have been on the rise in the past decade, yet are still not able to satisfy the patients' need of restoring lost upper extremity function. Many advancements have been made to develop new technology/devices to optimize/enhance the rehabilitation process in relation to comfort, interactive engagement of patients, price, size, portability, therapist feedback, and effectiveness. Contemporary solutions attempt to satisfy at least one of the listed criteria. However, this is very inefficient when looking at the broader scheme of rehabilitation.

Modern rehabilitation applies the principle of neuroplasticity to repetitive task practice training as the most effective means of

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treating the patient. Coupling this with wearable technology, such as devices that come in the form of gloves, patients with impaired hand mobility can bolster existing motoneuron connections and rewire their brains to develop new ones. Research shows that brain plasticity can be capitalized on to improve rehabilitation efforts and retrieve biological functionality.[7]

However, advanced technologies can potentially be used to increase rehabilitation accessibility to the patients, and it can be used to motivate patients for rehabilitation exercise.[8] It is evident from the recent research results[9] that the computer game–based rehabilitation solutions have the potential of integrating challenging environments/elements and offering motivation into the therapy routines, thereby increasing patient inspiration to follow through with previously tedious tasks. For these reasons, interactive computer gaming technology has gained attention as a component of rehabilitation. In past decades, Alankus et al,[9] Annet et al,[10] Shah et al,[11] and several others developed different types of game-based rehabilitation systems for the rehabilitation of human upper extremity. While novel ground work, these systems have room for improvement in ordr to make therapy more entertaining, engaging, user-friendly, and challenging.[12,13] It is worth noting that patients prefer to perform game-based rehabilitation exercises at home for long-term recovery.[14]

The literature review reveals that several hand rehabilitation devices have been recently developed to improve weakness, loos of coordination, or impaired dexterity. For example, Sasidharan et al[15] developed a smart glove with the use of resistive strip sensors to analyze the flexion and extension of the index finger and the wrist. During testing with this glove, many design flaws were noted and several were adapted during testing to improve the function of the glove. Results of the testing showed that the glove could detect wrist and index finger extensions but that the sensitivity had to be calibrated for each patient. Similarly, a group of researchers at the Sapienza University[16] used two LEAP Motion controllers positioned orthogonally to create a virtual glove to assist patients recovering from a stroke. They have used 3-dimensional multisensor technology to map the movement and function of the hand. However, the experimental data to observe the behavior of the system reveals, both in the infrared interferences and in the reference system roto-translation experiments, the discrepancy of the data was observed because of an intrinsic lack of accuracy of the LEAP sensor along the *Z* direction. Taking a mechanical approach to stroke recovery, Hong Kai et al[17] have developed a soft pneumatic glove. Their pilot test results reveal that the glove is able to provide grasping assistance to the hand to augment the stroke survivor's motion. Future work with this glove include adding objective measures such as force, range of motion (ROM), grip strength, and so forth. Recently, a group of researchers devised the MusicGlove[18] that is intended for the same purpose as the other projects listed. Using an interactive game–based therapy, the MusicGlove is a glove that senses the repetitive performance of pinching exercises and therefore it cannot provide individual/multifinger flexion/extension exercises. These are just a few of the many examples of research contributions to this area in the field within the past few years. A limitation in the majority of these examples is that they lack visual feedback to its users; flexibility of multifinger motion exercise; ability to provide the therapist with objective data such as individual's progress/recovery, increase of ROM, time taken to perform a functional task, and so forth. Thus, measures of how effective the therapy is to the patients reveal that enhanced motor learning occurs in the 'active rehabilitation therapy' mode, when patients (independently) practice a variety of functional tasks.[19] Therefore, in this research, we have developed a novel rehabilitation scheme with a game-interfaced sensored rehab glove. Our compact glove has the capability of engaging a patient playing a computer game (or a mobile phone game) that will record the data and put it in a format that could be easily read by a clinician or displayed to the clinicians in different graph formats. Some of the features of this glove include its portability, size, price, therapist feedback, and patient engagement.

In the next section of this article, a detailed overview of the design and development (hardware design/fabrication, electrical instrumentation, and software development) of the proposed sensored rehabilitation glove is presented. Experimental results with the developed *sensored rehab glove interfaced with a game* are presented in Experiment and Results section. Finally, the article ends with a conclusion and future research works in Conclusion section.

Sensored rehab glove

The proposed sensored glove is designed to be integrated with a computer game to engage patients in a therapeutic session where a patient plays a game during which single/multiple finger flexion/extension motions are required. The integrated system (sensored glove + game) provides (a) real-time data to the patients about their performance (eg, an increase of ROM) and (b) detailed analysis of the patient's progression to the therapist. The glove is designed for the patients to step outside of the therapist's office and still be able to proceed with the training exercises in a way that is motivating. However, therapists still play an integral part by monitoring their progress, directing them through the activities, and correcting the patient's mistakes during follow-ups.

Hardware design of proposed sensored rehab glove

When designing a device that will be used for a clinical purpose on individuals who lack certain abilities, it is crucial to adapt the design to the user's needs. Convenience, portability, and comfort were the three primary factors that we took into account during the development of the proposed sensored rehab glove. Typically, a glove is a garment (Fig. 1A) that covers the entire hand. Considering that we are working with the hand, it seemed most logical to use a glove. The glove that we have chosen fits each finger snug so that the flexing of each finger is most accurately represented through the bend in the glove. The glove is loose enough so that the hand can slide in with ease and there is minimal need for the gloved hand to cooperate while putting it on. Five flex sensors (one for each finger, as shown in Figs. 1A and 1B) have been instrumented on the glove to measure the flexion/extension of the finger.

Note that, we fabricated a small pocket onto each finger of the glove so that the flex sensor does not have any room to wiggle or slip out. These pockets were sewn closed to ensure that the flex sensors do not come out. For demonstration purpose, the flex sensors' instrumentation on the glove is illustrated in Figure 1A. An elastic Velcro strap at the wrist ensures that the glove stays on tight and does not move around as it is being used to play the game.

In a normally functioning hand, the metacarpophalangeal (MCP) joints are independent of the distal interphalangeal (DIP) and the proximal interphalangeal (PIP) joints. In addition, the DIP and PIP joints are both usually flexing simultaneously. Therefore, this type of sensor (Flex Sensor) is not entirely an accurate representation of the angle at which the finger is bending because it does not take each joint into consideration. Instead, the sensor detects overall flexion as shown in Figure 2. Therefore, the angle that the sensor reads could be interpreted as the combination of MCP, DIP, and PIP joint angles (for the thumb, it will be the combination of interphalangeal (IP) and thumb's metacarpophalangeal (MCPT)

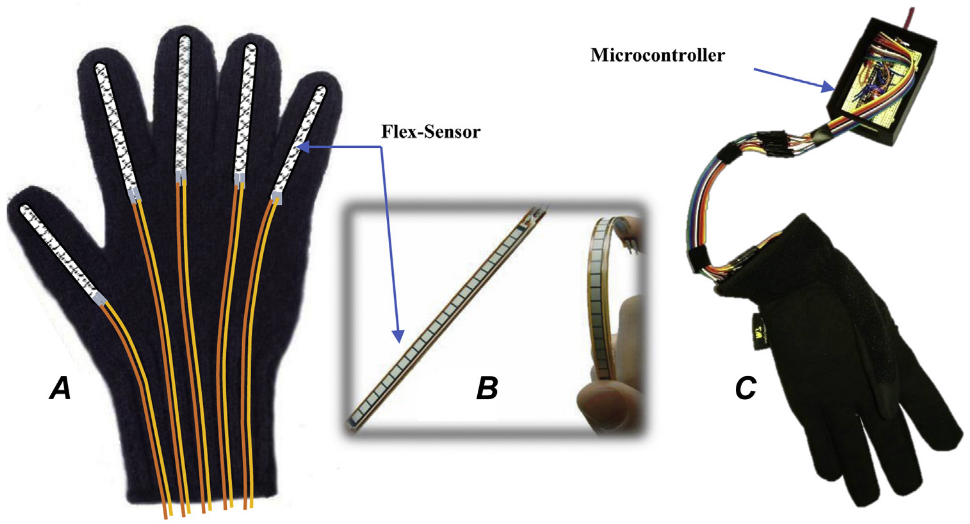

Fig. 1. Sensored glove system; **(A)** schematic of flex sensors instrumentation on the glove; **(B)** Flex sensor; and **(C)** developed sensored rehab glove with the circuitry open for display.

joint angles). Figure 2A shows the schematic of a flex sensor's resting state (angle 180°) and its fully flexed state (angle 0°).

Hard exoskeletal devices are commonly known for becoming uncomfortable after prolonged use. An experimental comfort assessment has shown that rigid devices create significant discomfort and limit the range of movement.[20] Similar to modern trends, we have fabricated the glove from soft materials, to ensure comfort throughout the training session. Essentially, when the glove is on the hand, the patient will not even realize it. Moreover, the utilization of a Bluetooth module, a compact design, and development of a versatile software make this very lightweight and portable. The developed sensored glove can be used at home so that repetitive task practice is maintained and the rate of neuroplasticity is maximized outside of the therapist's office.

Electrical and electronic design and instrumentation

The electronic hardware design is built on the Arduino Nano[21] open-source microcontroller as depicted in Figure 3. This made it easy to acquire flex sensor angles (ie, combined MCP, PIP, and DIP flexion/extension angles). Five resistive flex sensors are run through with a standard voltage of 5 V. As shown in Figure 2A, when a flex sensor is in its flat/resting orientation (ie, when the MCP, PIP, and DIP joints are in resting state as shown in Fig. 2B), it has a resistance of 25 KΩ. When the flex sensor is flexing (ie, when the finger is flexing), the resistance of the sensor increases; and in a fully flexed position of the sensor (ie, fully flexed position of a finger as shown in Fig. 2C), the resistance of the flex sensor increases to 125 KΩ, which is a 0° pinch bend as shown in Figure 2A. Therefore,

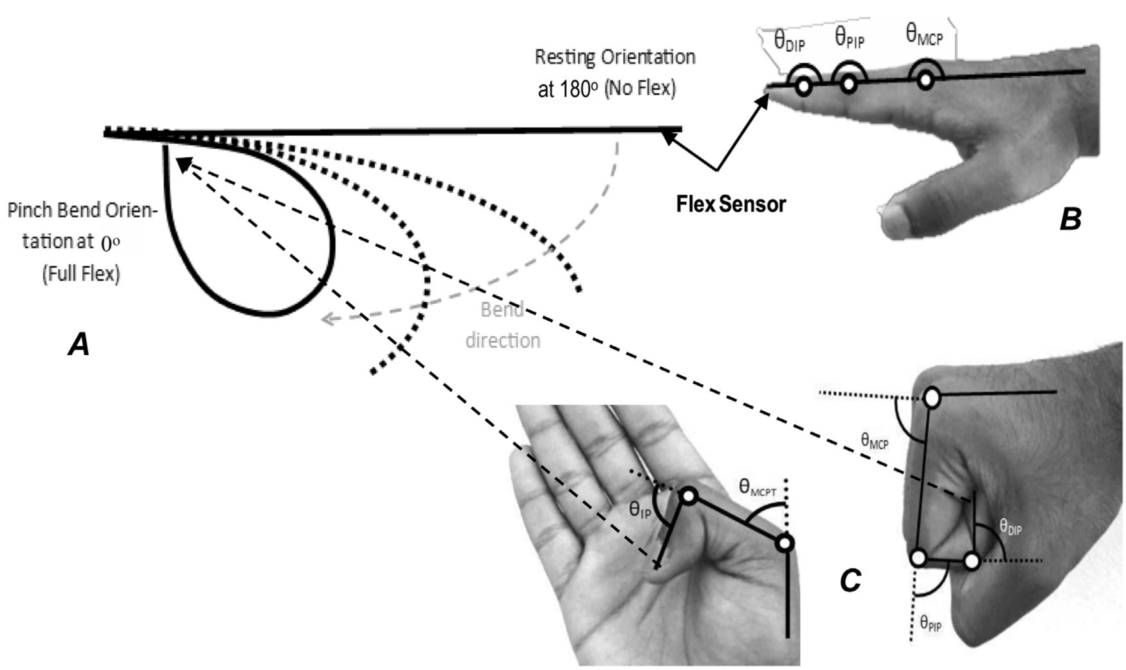

Fig. 2. MCP, PIP, and DIP flexion/extension estimation from flex sensor. **(A)** Schematic diagram of the resistive flex sensor shows the resting orientation (180°) and the fully flexed position (0°); **(B)** resting state of MCP, DIP, IP, MCPT, and PIP joints (where, $\theta_{MCP} = 180°$, $\theta_{DIP} = 180°$, and $\theta_{PIP} = 180°$); and **(C)** fully flexed position of MCP, DIP, PIP, IP, and MCPT joints (where, $\theta_{MCP} = 90°$, $\theta_{DIP} = 90°$, $\theta_{IP} = 90°$, $\theta_{MCPT} = 90°$, and $\theta_{PIP} = 90°$).

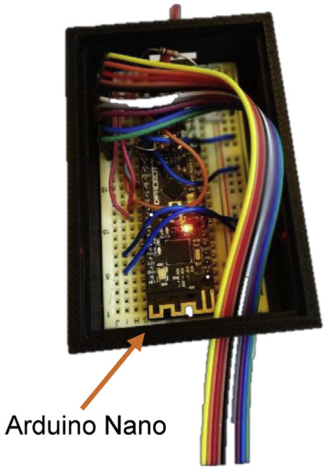

Fig. 3. Arduino, breadboard, and all electrical instrumentation housed in a 3D printed case.

this sensor is capable of capturing the full motions of both flexion and extension of individual fingers.

A Bluetooth module embedded Arduino Nano transmits the raw data from the glove's sensors to the USB dongle on the computer. As discussed previously, wireless communication between the glove and the computer makes the glove more convenient and eliminates the risk of tangled wires.

The utilization of a Bluetooth module proved to be as easy as creating a glove that was tethered to a computer (also can be tethered to a smartphone). The USB dongle is the receiver for the Bluetooth connection and receives all of the analog signals from the flex sensors representing flexion/extension of MCP/PIP/DIP joint angles. The Arduino Nano itself is the transmitter, sending the raw analog signals that are captured from the glove. The connection between these two devices automatically takes place once the dongle is in the USB port of the computer and the Arduino is switched on and connected to power, ultimately eliminating the need to pair the two Bluetooth devices. Note that, the raw analog signals acquired from the flex sensors are filtered before producing the desired results showing the flexion/extension angles of the fingers, *that is*, *our key objective measures of a therapeutic session using the developed sensored glove*.

Software design

There are two separate programs to the software side of this project, (a) the Arduino programming (microcontroller programming) and (b) the game-interface development. The first part of the program (Arduino programming) records the live (real-time) data from the glove of each finger's flexion/extension, sensed by the resistive flex sensors. These flex senor data are then converted and mapped to the corresponding finger flexion/extension angle. Later, the Arduino program compiles the mapped data along with a unique identifier and sends those to a separate program called *'Processing'*.[22] *Processing* is a language that was built based on the Java Language with simplified syntax. The *Processing* receives the data, parses the unique identifier from the numerical value, and stores it as an integer. The Flappy Bird game,[23] which was developed in *Processing*, is then able to easily interpret the finger flexion/extension angle through the basic logic and conditional statements. The *objective* of making this game is to drive the subjects to work/play with their fingers in a full ROM.

Flappy Bird is one of the most popular and addictive games-approximately 18 million people have played this game.[24] It is an open-source game that is why one can use its source code and modify it to add new features. In a traditional Flappy Bird type game, the player has full control over the bird's height. However, in our developed version, the user controls the bird's entrance in between the green tubes (see Fig. 4). It appeared very difficult to control the bird's flaps through the glove itself. Therefore, this alternative solution allows for simplicity for those with impaired, weak muscle function. When an individual (wearing the glove) starts a therapeutic session with this game, two green tubes and a name of a finger appear to play the game (Fig. 4). The individual must bend (flex/extend) that finger completely to the best of their ability to lift the bird to a height in between the green tubes as the bird crosses the tubes. As shown in Figure 4A, the game asks the player to flex her pinky finger to the best of their ability. Each successful attempt at bending the finger while crossing the tubes will result in their score to increase by one. However, if the individual fails to bend (flex/extend) that particular finger within an allowable range, then the game will end and their score will be displayed. Also, if the individual bends (flex/extend) other fingers beyond the allowable range, the game will end immediately showing *'wrong finger movement.'* Therefore, a player can not cheat the game. For instance, in Figure 4C, the player did not flex the ring

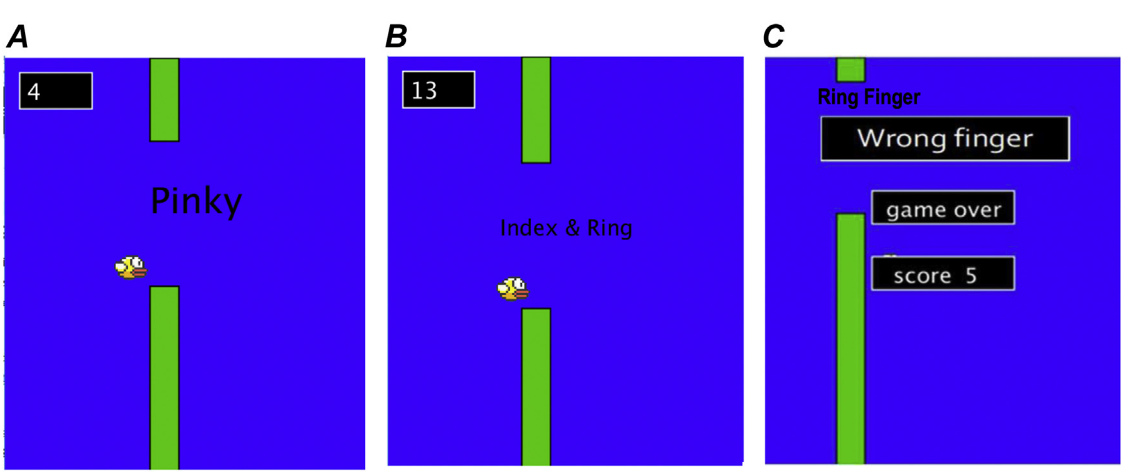

Fig. 4. Three screenshots of the game are presented to show what the game looks like and how it functions. **(A)** This screenshot depicts a player with a score of 4 points, and the game asks the player to flex her pinky finger; **(B)** this screenshot presents a multifinger motion exercise that the player must perform; **(C)** this screenshot shows the game has ended after the player made an error.

finger and, therefore, the game ended. The goal is to make an entertaining and engaging environment of providing therapeutic exercise for individuals with loss of motor function in the hand. Therefore, the game gets progressively more difficult as the player advances through the game. For example, in our default setting, if a player scores 10, the game will require him/her to coordinate with more than one finger. This case is presented in Figure 4B as the game requires the player to flex both their index and ring finger simultaneously. The program includes all possible combinations of two fingers and multifinger flexion/extension motions. This allows for the patient to perform complex finger motions when they are suited to go to that stage. The game can be played either on a computer or on a feature phone/smartphone/tablet. Provisions included in the game (a) to set up the time limit, or allow players to play as long as they want; (b) customize the difficulty level threshold (default setting is *level 1* for score less than 10; *level 2*: scores from 10 to 20; *level 3*: score >20); (c) customize the single and multifinger repetitions (default setting is randomly selected); (d) slow/speed up the game (to facilitate slow or fast flexion/extension of finger); and (e) reverse the game control for poststroke patients with flexure contractures where an individual must *extend* his/her finger completely to the best of their ability to lift the bird to a height in between the green tubes as the bird crosses the tubes.

Each time a patient plays the game, the score will be recorded in a file that the therapist can access. This provides the patient with information such as the maximum degrees the finger was bent, the minimum it was bent, the score of each game, and the date/time the game was played. The physical or the occupational therapist may use this information to track the patient's progress over time to evaluate the extent to which the patient has progressed and benefited through the therapy.

Experiment and results

The glove concept is based on the idea that exercises that engage individuals during the practice of motor activities are often beneficial for neurorehabilitation as shown through numerous studies.[25] When these practices are implemented with repetition and complexity, they prove to be effective.[26] The entire outline of the therapeutic process with the glove is illustrated in Figure 5. An individual will play an open-source game named Flappy Bird wearing a sensored glove. The game was adapted and customized for the developed sensored glove system. The glove will wirelessly transmit experiment data (ie, the flex-sensor signals) to the computer/smartphone (where the game runs) as the control input for the game. As mentioned earlier, the flex sensors are attached to each finger of the glove and provide the flexion/extension information of the finger. As shown in Figure 5, this information is then interpreted by the program and converted into a flexion/extension angle (in degrees) that the finger is bent to identify the instantaneous position of the fingers. In the game interface, the flexion/extension angle determines the flying height of the bird on the screen. Moreover, this position information of the fingers will allow the computer to determine whether the user is performing the task with accuracy. If the accuracy is poor, then the game interface will provide visual feedback to the user alerting them that they have made a mistake. The session data are compiled and placed in a log file. This log will be used by the therapist to analyze the patient's performance and make any adjustments as needed.

To demonstrate the proof of concept (as well as to evaluate the performance of the developed *'game-interfaced sensored glove system'*), an experiment was designed with three healthy subjects (subject 1: age 17 years (male); subject 2: age 37 years (female); and subject 3: age 44 years (male)).

When considering the presented data, it should be noted that each individual possessed varying video game experience. In addition, because the subjects of the experiment were healthy and possessed no physical disabilities, the performance would theoretically be much better than that of a patient. This game was designed for those with motor disabilities; thus, the simplicity of the game was of high priority. Therefore, the results themselves should not be considered with high importance. The subjects put the glove on and played the game ten times each. Results were then plotted on a graph showing the dates/time and the duration the game was played, the score that they received, and the complete history of fingers flexion/extension angles. Figure 6 display the score that subjects received after they had played the game each day. Tables 1–3 were obtained from the data log of the game. From this data log, a therapist can monitor how often a patient has participated in the game (therapeutic session), the time he/she spent in the sessions, and so forth. As shown in Figure 6A, subject 1 did not play the game on March 31st. Also, it will help the therapist

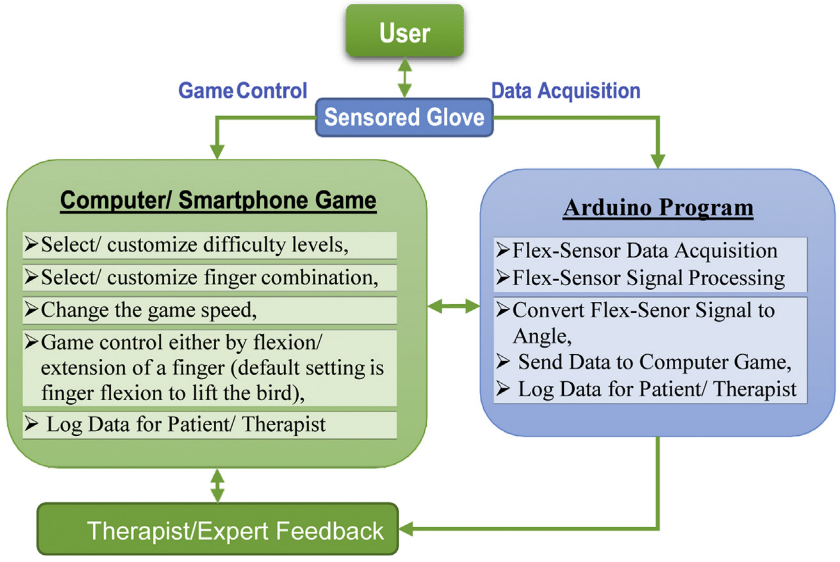

Fig. 5. Block diagram showing an overview of how the therapeutic process with the developed sensored glove works.

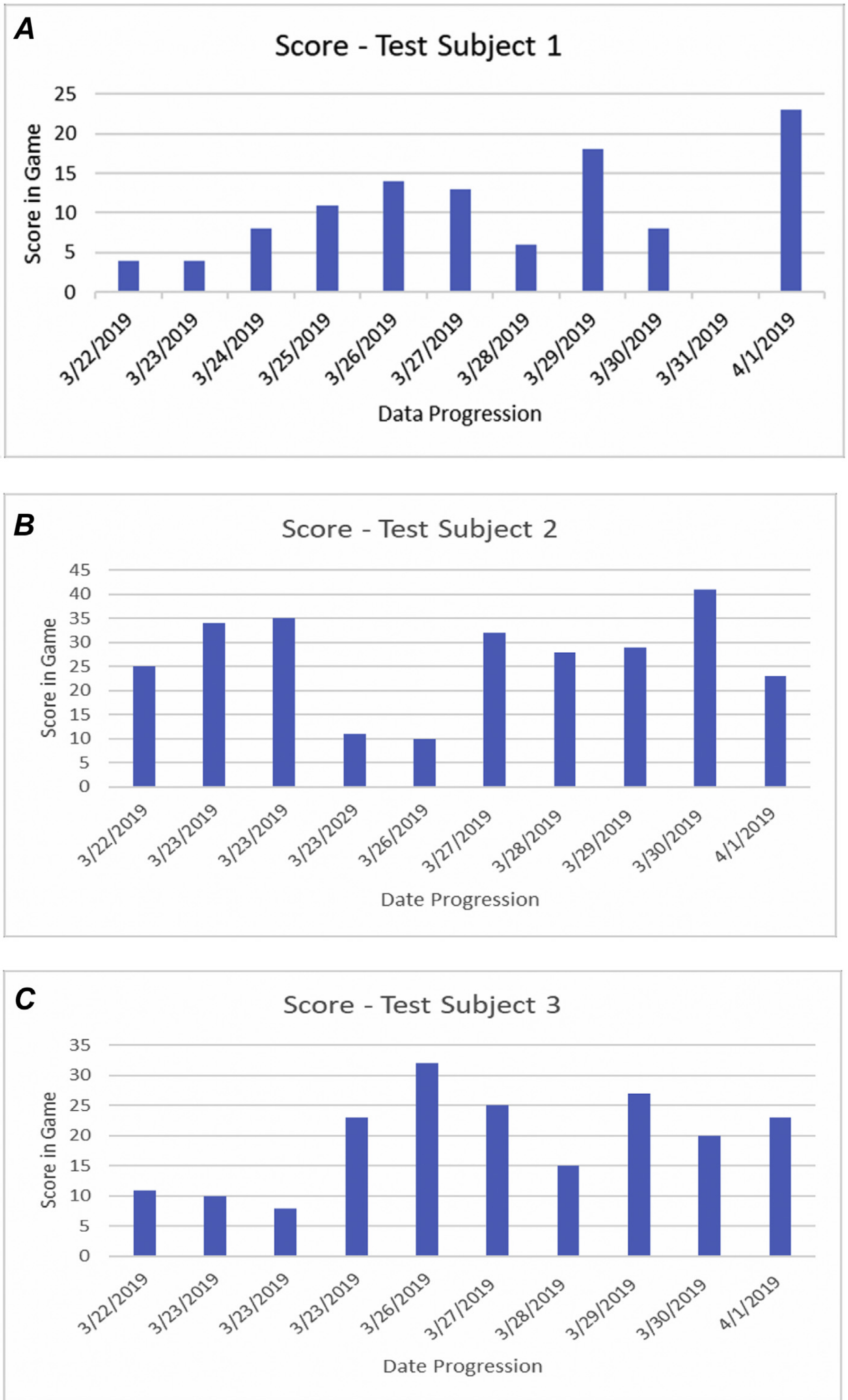

Fig. 6. The game score received throughout the 10 days, **(A)** subject 1's logbook; **(B)** subject 2's logbook, and **(C)** subject 3's logbook.

to track the progress of the patients. Here, in Figure 6A, a slight upward trend could be noticed; this may be the result of a better understanding of the game over time. The data are presented simply to demonstrate how the patient's progress will be tracked and how the therapist could potentially interpret this information.

From the data log, a therapist can *quantitatively measure the subject's progress* by analyzing the subject's finger flexion/extension angles for each session the subject has played the game. Experimental results of three different subjects playing the game are shown in Figures 8-11, where subjects' finger flexion/extension angles are plotted from the data log of a few randomly selected game sessions. Figure 7 explains how to interpret the results of Figures 8-11. It can be seen from Figure 7 that a plot (dotted line) from the area of red line (180°) toward the green line (0°) indicates the finger has bent from its extension position (180°) to flex position (0°), whereas a plot (dotted line) from the area of green line

Table 1
Game score of subject 1

Date	Score
3/22/2019	4
3/23/2019	4
3/24/2019	7
3/25/2019	11
3/26/2019	14
3/27/2019	13
3/28/2019	6
3/29/2019	18
3/30/2019	8
4/1/2019	23

Table 3
Game score of subject 3

Date	Score
3/22/2019	25
3/23/2019	34
3/23/2019	35
3/23/2029	11
3/26/2019	10
3/27/2019	32
3/28/2019	28
3/29/2019	27
3/30/2019	41
4/1/2019	23

(0°) toward the red line indicates the finger has bent from its flexed position (0°) to extension position (180°).

As mentioned earlier, the proposed rehabilitation scheme can be facilitated both for finger flexion and extension movement in the game. Figure 8 shows the experimental results, where the subject conducts finger extension motion (to lift the bird) to play the game. Whereas, in Figures 9 and 11, the subjects perform finger flexion motion (to lift the bird) to play the game. Based on the subject's finger impairment, a therapist can prescribe the flexion or extension motion the subject should choose to play the game. As shown in Figure 8B, all the scoring finger movement (seven times, as shown in Fig. 8B) occurred when joint angle moves from near 0° to near 180° degree and all initial joint angles are in near 0°, which indicates finger motion from flexed position toward an extension. Whereas in Figures 9 and 11, a reverse finger motion produces a score, that is, finger flexion motion from its extension position will produce a score. Note that, in our default game setting, instruction for multifinger motion appears when a subject reaches a score of 10, but provision has been included in the game to change the difficulty level threshold as desired (by the therapists/subjects). Game difficulty levels are described in the following:

- Difficulty level 1: This is our default game setting for a score of less than 10. At this setting, a random finger name appears on the screen. The subject must flex/extend that finger to play the game.
- Difficulty level 2: When a subject scores 9, the default setting of the difficulty level moves to the level 2, where two fingers' simultaneous movement is required to play the game. At this setting, a random combination of two fingers' names appears on the screen. The subject must flex/extend those two fingers to play the game.
- Difficulty level 3: When a subject scores 20, the default setting of the difficulty level moves to level 3, where three fingers' simultaneous movement often required to play the game. At this setting, a random combination of three fingers' names often appears on the screen. The subject must flex/extend those three fingers to play the game.

Table 2
Game score of subject 2

Date	Score
3/22/2019	25
3/23/2019	34
3/23/2019	35
3/23/2029	16
3/26/2019	10
3/27/2019	32
3/28/2019	28
3/29/2019	29
3/30/2019	41
4/1/2019	23

From Figure 8B, it is clearly evident that there were seven instances in that session where finger extension motion happened as can be seen from the seven peaks which have resulted in a score of 7. It can be also observed from Figure 8B that there were no overlapping peaks in that session, that is, there is no simultaneous motion of multifingers involved in that session.

Experimental results with subject 2 are presented in Figures 9 and 10. The Figure 9 demonstrates a different scenario where simultaneous motions of two fingers (index and pinky) toward the complete flexion motion are observed in the game (for the first time) around at 26 sec (as evident from the overlapping double peaks) when the subject reached the difficulty level 2, that is, after scoring points 9 (ie, after 9 nonoverlapping peaks). A few more two fingers' simultaneous movements but with the different combinations of two fingers are observed from 26 sec to 45 secs (as evident from the double peaks, scores: 10-16). Figure 10 shows the results of the same experiments presented in Figure 9, but the results are plotted separately for one finger flexion/extension motion in Figure 10A, and two fingers' simultaneous flexion/extension motion in Figure 10B.

Experimental results with subject 3 are presented in Figure 11, where a simultaneous motion of three fingers has appeared (at around 64 sec) when the subject reached the difficulty level 3 (ie, after scoring the 20 points). It is also seen (in Fig. 11) as the score increased, not only the complex finger combination appeared on the game but also the speed of the game increased, thus providing a more challenging environment to the participant. Note that, a therapist can set the speed of the game for different score levels, or set up a steady speed for all the levels depending on the patient's condition.

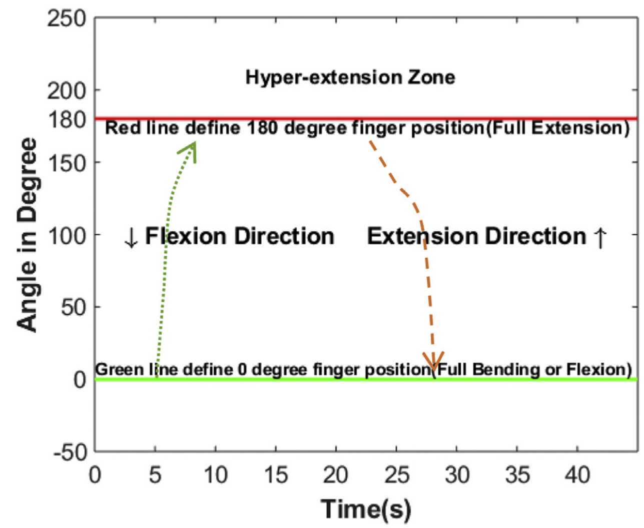

Fig. 7. Nomenclature for data representation.

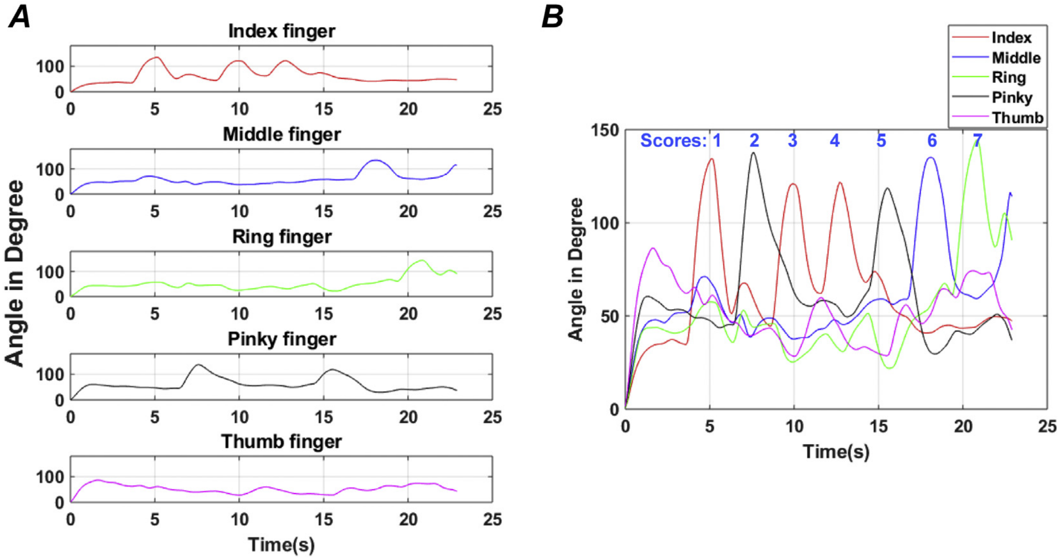

Fig. 8. The experimental result with subject 1 scored 7 on March 24th for finger extension movement; **(A)** individual finger movement plots; **(B)** results shown in panel **(A)** are plotted in one graph. No simultaneous motion of multifingers can be seen on panel **(B)** as the subject's score was less than 10.

It is obvious from all the results (Figs. 8, 9, and 11) that for a particular finger motion, a few other fingers also show some movements. This is due to the dependence of a finger motion on other fingers. For a stroke patient, this dependence will be much more severe. In this rehabilitation scheme, the developed game includes some provisions where a therapist can adjust how much flexion/extension movements of the dependent finger should be allowed for a particular patient so that the game can go on without showing *'wrong finger movement'* (an example of this case is presented in Fig. 4C). The therapist also needs to define the amount of flexion/extension angle for the fingers of the patient to consider as a successful flexion/extension to lift the bird in the game. In our experiments, we have considered a finger flexion/extension angle greater than 60° as a successful movement to play the game, and the dependent finger movement should be less than 50°, otherwise the game will end with the message *'Wrong Finger.'*

Experimental results presented in Figures 8-11 reveal that the developed rehab glove system can be effectively used to engage an individual in playing a computer game (or a mobile phone game) that can record the data (ie, game score, finger flexion/extension angle, time spent in a therapeutic session, etc.) and put it in a format that could be easily read by a therapist or displayed to the therapists/patients in different graph formats.

Conclusion

In this article, we presented an engaging rehabilitation method for individuals with hand dysfunction. A sensored glove was developed to detect finger flexion/extension motion and was integrated with a computer game named 'Flappy Bird.' The game has been customized to play with the developed sensored glove. The glove wirelessly sends the finger flexion/extension data to the game. In a therapeutic session, an individual plays the game by flexing/extending his or her fingers. Based on the user's performance/progress (game score determines the performance) the difficulty level of the game changes intelligently to engage the user with the

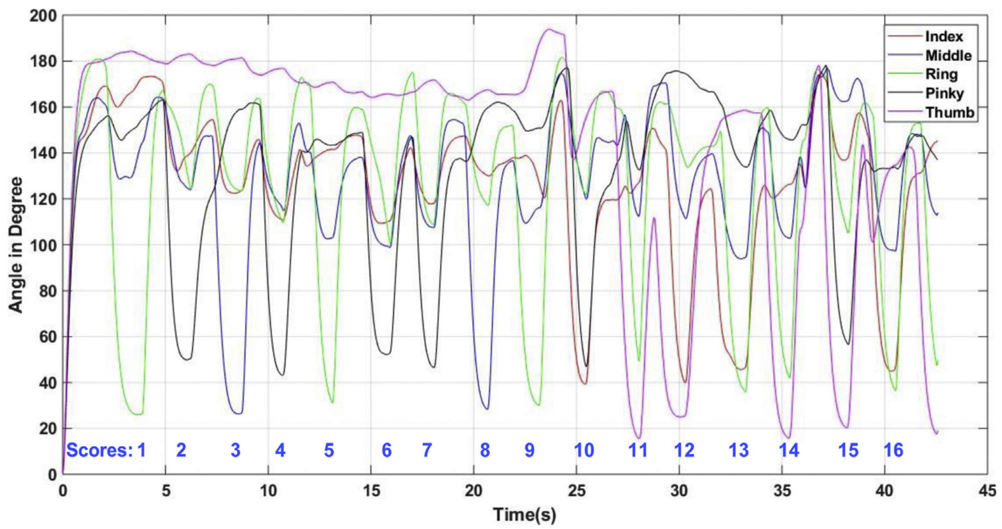

Fig. 9. The experimental result with subject 2 scored 16 for the finger flexion movement. A double finger combination appeared on the figure after the subject's score reaches 10.

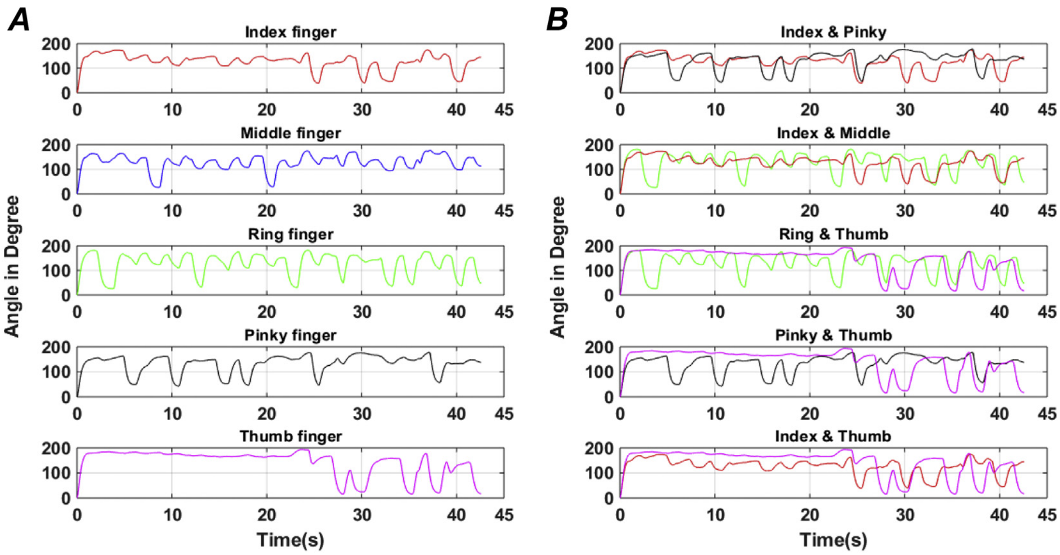

Fig. 10. **(A)** Individual finger joint angles extracted from Fig. 9; **(B)** simultaneous flexion motion of two fingers extracted from Fig. 9.

more challenging tasks (where multifinger motions are required to play the game). The game can be played either on a computer or on a smartphone. Provisions included in the game (a) to set up the time limit; (b) customize the difficulty level; (c) customize the single and multifinger repetitions; (d) slow/speed up the game (to facilitate slow or fast flexion/extension of finger); and (e) reverse the game control for poststroke patients with flexure contractures where an individual must *extend* his/her to play the game. To demonstrate the proof of concept (as well as to evaluate the performance of the developed *'game-interfaced sensored glove system'*), an experiment was conducted with the healthy subjects where the users play the developed game wearing the sensored glove. In the experiments, subjects' finger joint flexion/extension angle and game scores are recorded. Experimental results reveal that the developed rehab glove system can be effectively used to engage a patient playing a computer game (or a mobile phone game) that can record the data (game score, finger flexion/extension angle, etc.) and put it in a format that could be easily read by a therapist or displayed to the therapists/patients in different graph formats.

The developed system will enable the therapists to monitor the patient's progress through the player's score in the game that is recorded in a progressive log. This method of rehabilitation rests on the idea that through repetitive task practice and through making the patient attempt progressively more complex hand positions, they will undergo neuroplasticity at a faster rate and regain dexterity in each individual finger. In addition, by being able to continue the progress and play the game at home, therapeutic sessions are not confined to the therapist's office. Most importantly, with this method of therapeutic approach, patients will avoid potentially monotonous tasks and remain engaged in their rehabilitation.

In future work, a study with actual patients who suffer from a motor impairment of the upper limb will be conducted over an extended period of time. Experiments using test subjects rather than healthy controls will allow for better feedback on the efficiency of the glove. In addition, we will expand the software to make the glove compatible with a variety of more engaging video games. Eventually, incorporating virtual reality games would make the treatment process more engaging and potentially even make

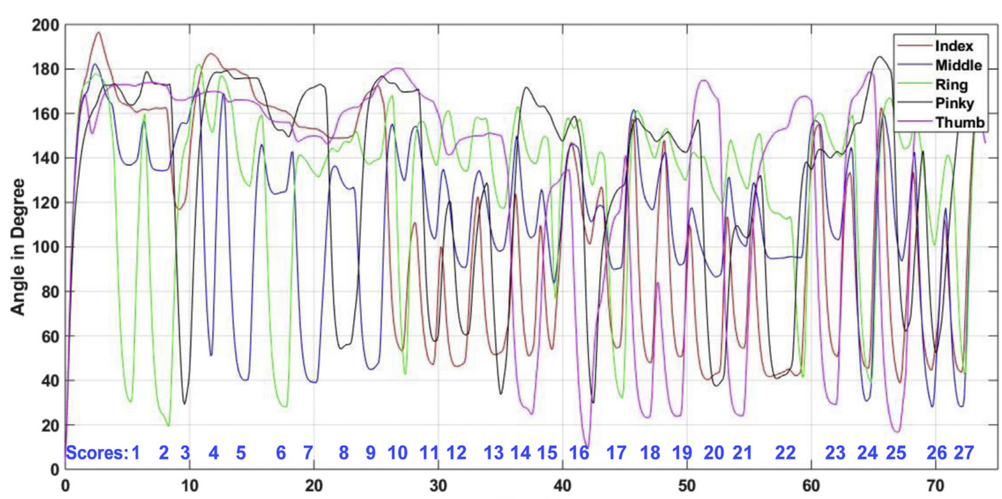

Fig. 11. The experimental result with subject 3 scored 27 for finger flexion movement. Double and triple finger combination appeared on the figure after the subject's score increases.

rehabilitation more efficient. As this glove is developed, long-term studies will be performed to determine the efficiency, successes, and drawbacks of this type of repetitive task practice training for hand rehabilitation.

CRediT authorship contribution statement

Vinesh Janarthanan: Investigation, Writing - original draft. **Md Assad-Uz-Zaman:** Writing - original draft, Formal analysis, Investigation. **Mohammad Habibur Rahman:** Writing - original draft, Formal analysis, Investigation. **Erin McGonigle:** Writing - original draft, Formal analysis, Investigation. **Inga Wang:** Writing - original draft, Formal analysis, Investigation.

References

1. Benjamin EJ, Michael JB, Stephanie EC, et al. Heart disease and stroke statistics-2017 update: a report from the American Heart Association. *Circulation*. 2017;135(10):e146–e603.
2. Mackay J, Mensah G. *Atlas of Heart Disease and Stroke*. Brighton, UK: World Health Organization, Nonserial Publication; 2004.
3. Parker VM, Wade DT, Langton HR. Loss of arm function after stroke: measurement, frequency, and recovery. *Int Rehabil Med*. 1986;8(2):69–73.
4. Education USD of. In: *USA 1983-1986: From the Digest of Data on Person with Disabilities*. Washington, DC: US Department of Education, National Institute on Disability and Rehabilitation Research; 1992.
5. Marty J, Porcher B, Autissier R. Hand injuries and occupational accidents. Statistics and prevention. *Ann Chir Main*. 1983;2(4):368–370.
6. Jenkins JA. Caregiving costly to family caregivers. Available at: https://www.aarp.org/caregiving/financial-legal/info-2017/family-caregiving-costly-jj.html; 2018. Accessed November 18, 2019.
7. Kleim JA, Jones TA. Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *J Speech Lang Hear Res*. 2008;51(1):1092–4388.
8. Wood SR, Murillo N, Bach-y-Rita P, Leder RS, Marks JT, Page SJ. Motivating, game-based stroke rehabilitation: a brief report. *Top Stroke Rehabil*. 2003;10(2):134–140.
9. Alankus G, Lazar A, May M, Kelleher C. *Towards Customizable Games for Stroke Rehabilitation*. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 2113-2122. New York, NY: Association for Computing Machinery; 2010.
10. Annett M, Anderson F, Bischof WF. *User Perspectives on Tabletop Therapy*. Proceedings of the 9th International Conference on Disability, Virtual Reality & Associated Technologies (Laval, France, 2012). 2012.
11. Shah N, Amirabdollahian F, Basteris A. *Designing Motivational Games for Stroke Rehabilitation*. Human System Interactions (HSI), 2014 7th International Conference on IEEE. 2014:166–171.
12. Shah N, Basteris A, Amirabdollahian F. Design parameters in multimodal games for rehabilitation. *Games Health J*. 2014;3:13–20.
13. Anderson KR, Woodbury ML, Phillips K, et al. Virtual reality video games to promote movement recovery in stroke rehabilitation: a guide for clinicians. *Arch Phys Med Rehabil*. 2015;5:973–976.
14. Hung Y-X, Huang P-C, Chen K-T, Chu W-C. What do stroke patients look for in game-based rehabilitation: a survey study. *Medicine (Baltimore)*. 2016;95(11):e3032.
15. Sasidharan S, Smart Glove. An Assistive Device to Enhance Recovery of Hand Function During Motor Rehabilitation. In: *Master's thesis*. Arizona State University; 2015:62.
16. Placidi G, Luigi C, Andrea P, Matteo P, Matteo S. *A Virtual Glove System for the Hand Rehabilitation Based on Two Orthogonal LEAP Motion Controllers*. Proceedings of the 6th International Conference on Pattern Recognition Applications and Methods. Portugal: Porto; 2017.
17. Yap HK, Jeong HL, Fatima N, Chen-Hua Y. Design and preliminary feasibility study of a soft robotic glove for hand function assistance in stroke survivors. *Front Neurosci*. 2017;11:547.
18. Zondervan DK, Nizan F, Enoch C, et al. Home-based hand rehabilitation after chronic stroke: randomized, controlled single-blind trial comparing the MusicGlove with a conventional exercise program. *J Rehabil Res Dev*. 2016;53(4):457–472.
19. Winstein CJ, Merians AS, Sullivan KJ. Motor learning after unilateral brain damage. *Neuropsychologia*. 1999;37(8):975–987.
20. Levesque L, et al. *Experimental Comfort Assessment of an Active Exoskeleton Interface*, 2017 IEEE International Symposium on Robotics and Intelligent Sensors (IRIS). 2017.
21. Getting Started with the Arduino Nano, arduino.cc. https://www.arduino.cc/en/Guide/ArduinoNano, Accessed 18 November 2019.
22. Reas, Casey, and Ben Fry. *Processing: a programming handbook for visual designers and artists.*. Cambridge, MA: Mit Press; 2007.
23. Nguyen D. *Flappy Bird Game*; 2013. From: https://www.ign.com/games/flappy-bird. Accessed November 18, 2019.
24. Peckham M. No, you don't have to play Flappy bird". Available at: https://time.com/4034/no-you-dont-have-to-play-flappy-bird/; 2014. Accessed November 18, 2019.
25. Petzinger GM, Fisher BE, McEwen S, Beeler JA, Walsh JP, Jakowec MW. Exercise-enhanced neuroplasticity targeting motor and cognitive circuitry in Parkinson's disease. *Lancet Neurol*. 2013;12(7):716–726.
26. Barrett N, Swain I, Gatzidis C, Mecheraoui C. The use and effect of video game design theory in the creation of game-based systems for upper limb stroke rehabilitation. *J Rehabil Assist Technol Eng*. 2016;3, 2055668316643644.

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Home-based hand rehabilitation after chronic stroke: Randomized, controlled single-blind trial comparing the MusicGlove with a conventional exercise program

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Abstract—Individuals with chronic stroke have limited options for hand rehabilitation at home. Here, we sought to determine the feasibility and efficacy of home-based MusicGlove therapy. Seventeen participants with moderate hand impairment in the chronic phase of stroke were randomized to 3 wk of home-based exercise with either the MusicGlove or conventional tabletop exercises. The primary outcome measure was the change in the Box and Blocks test score from baseline to 1 mo posttreatment. Both groups significantly improved their Box and Blocks test score, but no significant difference was found between groups. The MusicGlove group did exhibit significantly greater improvements than the conventional exercise group in Motor Activity Log Quality of Movement and Amount of Use scores 1 mo posttherapy ($p = 0.007$ and $p = 0.04$, respectively). Participants significantly increased their use of MusicGlove over time, completing 466 gripping movements per day on average at study end. MusicGlove therapy was not superior to conventional tabletop exercises for the primary end point but was nevertheless feasible and led to a significantly greater increase in self-reported functional use and quality of movement of the impaired hand than conventional home exercises.

Clinical Trial Registration: ClinicalTrials.gov; "Influence of Timing on Motor Learning"; NCT01769326;
https://clinicaltrials.gov/ct2/show/NCT01769326

Key words: hand impairment, hand therapy, home therapy, Motor Activity Log, music therapy, randomized controlled trial, rehabilitation, stroke, task-specific rehabilitation, virtual reality.

INTRODUCTION

Hand impairment after stroke contributes substantially to disability in the United States and around the world [1]. Intensive movement practice can reduce hand impairment [2–6], but issues such as cost and access may limit the dose of rehabilitation exercise delivered one-on-one with a therapist. Because of these and other factors, most individuals do not perform the large number of exercise repetitions required during therapy to maximize recovery [7–8]. Home-based rehabilitation programs may be prescribed after stroke with the intent to increase the amount of rehabilitation exercise individuals perform. However, the most common approach to home-based hand therapy is following a printed handout of exercises. This approach is often not motivating and thus is associated with low compliance and high dropout rates [9–13].

Abbreviations: ANOVA = analysis of variance, AOU = Amount of Use, ARAT = Action Research Arm Test, MAL = Motor Activity Log, QOM = Quality of Movement.

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To address this problem, other types of home-based rehabilitation programs for the hand have been proposed. For example, one pilot study explored a modified form of constraint-induced movement therapy performed under the supervision of a nonprofessional coach in the home and found similar benefits to the same program performed with a trained therapist in a clinic [14]; a larger study using this protocol found that home-based constraint-induced movement therapy led to significantly greater self-reported use of the impaired limb than conventional therapy [15]. Another common approach is telerehabilitation, which allows a therapist to guide therapy remotely [16]. While this approach is gaining popularity, a recent Cochrane systematic review of 10 trials with 933 total participants found limited evidence to support its use and no studies that examined its cost-effectiveness [17]. Other approaches to home-based hand rehabilitation include functional electrical stimulation [18], computer gaming with custom devices [19–21], and music-based therapy [22]. However, despite the variety of options, few home-based programs have been tested in controlled studies [23]. Further, it is still unclear which methods are the most effective and efficient means of providing an increased dose of rehabilitation, though the use of computer games and music has been found to be highly motivating [20,24–26].

We developed the MusicGlove, an instrumented glove with sensors on each of the fingertips and the lateral aspect of the index finger. The MusicGlove requires the user to practice functional gripping movements by touching the sensor on the tip of the thumb to one of the other five sensors in time with music through a video game that displays scrolling notes on a screen (**Figure 1**). In previous pilot studies performed in a clinical setting, we found that the MusicGlove motivated individuals with chronic stroke to perform hundreds of functional gripping movements during a 30 min training session and that exercise with the device led to a significantly greater improvement in hand grasping ability, measured with the Box and Blocks test, than a time-matched dose of conventional tabletop therapy performed with a rehabilitation therapist [27–28]. The individuals who used the MusicGlove also reported that the exercise was more motivating than conventional therapy and expressed interest in using the device to exercise at home. An important question, therefore, was whether self-guided exercise with the MusicGlove performed at home is feasible and improves hand function compared with conventional home therapy.

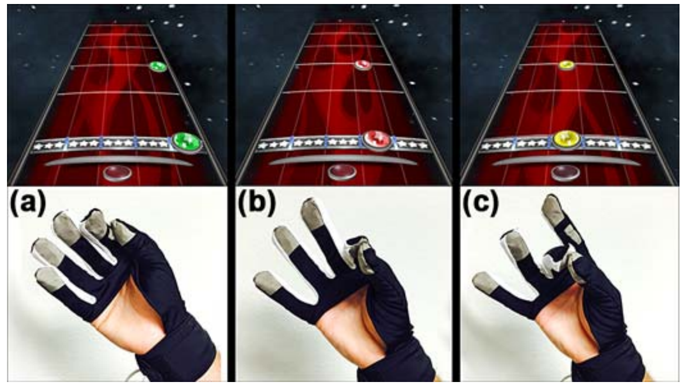

Figure 1.
MusicGlove device used in study. Users are visually cued by scrolling notes on screen (top) to make specific grips in time with popular songs, similar to the video game Guitar Hero. Grips include **(a)** key pinch grip; **(b)** pincer grip; and **(c)** finger-thumb opposition with second, third, and fourth fingers. During gameplay, the user must complete the cued grip when a colored note passes over the starred strip shown at bottom of the game screen (time window of about 800 ms). If the user is successful, the colored note disappears, providing visual feedback. If the user is unsuccessful, a beep is played, providing auditory feedback.

To address this question, we performed a randomized, controlled single-blind trial that compared home-based training with the MusicGlove to home-based conventional tabletop training directed using a pamphlet of hand exercises. We hypothesized that the participants in the MusicGlove therapy group would improve their hand function more than the participants in the conventional therapy group when assessed 1 mo after treatment.

METHODS

Study Design and Inclusion Criteria

This study was a home-based randomized controlled trial that compared self-guided exercise with the MusicGlove to self-guided conventional tabletop therapy for individuals in the chronic phase of stroke. The study protocol was approved by University of California at Irvine's Institutional Review Board and registered at ClinicalTrials.gov (#NCT01769326). All participants provided informed consent. Inclusion criteria were one or more strokes with onset >6 mo prior to the study, Box and Blocks score of at least 1, ability to understand the instructions for the home exercise programs, and age <75 yr.

Exclusion criteria were severe pain in the affected upper limb measured as a score >5 in the visual analog pain scale, severe tone in the affected upper limb measured as a score >3 in the Ashworth Scale of Spasticity for the wrist and elbow, severe loss of sensation of the affected upper limb measured as a score <10 in the Fugl-Meyer Sensory Examination, concurrent severe medical problems, visual deficits, severe neglect or apraxia, and enrollment in other upper-limb therapy studies.

Outcome Measures

All assessments were performed at the University of California at Irvine by two blinded, experienced evaluators. The primary end point was the change in Box and Blocks score, which measures how many blocks a subject can pick up and place in a box in 60 s [29–30], from baseline to 1 mo posttherapy. Secondary end points included changes in the Quality of Movement (QOM) and Amount of Use (AOU) subscales of the Motor Activity Log (MAL) [31–32], which is a structured interview that asks subjects to rate how well and how much they use their upper limb in performing 30 activities of daily living outside of the laboratory; the Nine Hole Peg test [33], which measures how many pegs a subject can put in and remove from holes in 60 s; and the Action Research Arm Test (ARAT), which assesses the ability to manipulate various sized objects with the impaired arm and hand [30,34].

The following tests were also administered at baseline to characterize subjects: the Geriatric Depression Scale [35]; the upper-limb section of the Fugl-Meyer score [36], which measures impairment of the hemiparetic upper limb; the National Institutes of Health stroke scale [37]; and the modified Ashworth spasticity scale for the wrist [38]. These measures have established excellent sensitivity and reliability.

Interventions

All participants were invited for an initial assessment to confirm that they met the inclusion criteria and to establish their baseline characteristics. Those who met the inclusion criteria were instructed to return 1 wk later for a second assessment to measure whether they had a stable baseline. Repeating the baseline assessments also accounted for familiarization or learning effects that could distort gains from true recovery [39–40]. At this time, the participants were randomly assigned to either the MusicGlove therapy group or conventional therapy group (i.e., the control group). To ensure matched levels of impairment between groups, subjects were first stratified by their second Box and Blocks baseline score (0–30 or 30–60) and then randomized by alternating block allocation, a technique referred to as adaptive randomization [41].

Participants randomized to the MusicGlove therapy group were given a MusicGlove device and a laptop with the software preinstalled. The MusicGlove devices used in this study were manufactured by Flint Rehabilitation Devices. They received a 15 min instruction on how to put on and use the device and how to operate the accompanying software. Participants in the conventional therapy group were given a booklet of tabletop exercises for home therapy of the hand developed by experienced occupational therapists and implemented in a prior clinical trial [42] and were instructed on how to correctly perform each hand exercise (see **Appendix**, available online only). Both groups were asked to perform self-guided therapy for at least 3 h/wk over at least three sessions per week, for three consecutive weeks, for a total of 9 h of therapy; such a dose had been found previously to be sufficient to induce significant improvements in hand movement ability [8,43–45]. Both groups were also asked to manually record the amount of time they spent performing their self-guided therapy on a written exercise log. The laptops provided with the MusicGlove also recorded the number of grips completed with the device. The participants were contacted by a research therapist or nurse at least once a week to address any potential technical difficulties and to ensure there were no adverse health effects from the prescribed therapy.

After the 3 wk exercise period, the participants returned for posttherapy assessments. At this assessment, participants in the MusicGlove group returned the device, and participants in the conventional therapy group were instructed to discontinue their exercises. Participants then returned 1 mo later for follow-up assessments.

Crossover

As part of a secondary aim, participants in the conventional therapy group were given a MusicGlove device and laptop and instructed on how to use it after the 1 mo posttherapy assessment. These participants were asked to repeat the same therapy regimen (3 h/wk for 3 wk) using the MusicGlove to exercise at home. At the end of this crossover exercise period, these participants returned for posttherapy assessments and returned the device. They again returned 1 mo later for follow-up assessments.

Data Analysis

We anticipated an effect size of MusicGlove therapy of 1.11 based on an independent samples *t*-test immediately after therapy in our initial pilot study [27]. Thus, 11 participants in each group would provide an 80 percent chance to demonstrate a significant difference between the MusicGlove and control therapies at the 0.05 significance level (one-tailed).

Two-tailed Student *t*-tests (for continuous data) and Fisher exact tests (for categorical data) were used to compare baseline measures between the two treatment groups. For each of the outcome measures, if there was no significant difference in the group mean from the first to the second baseline, we calculated the individual changes at each follow-up assessment as the difference from the average of the two baseline values. If there was a difference in the group mean between baseline assessments for a particular outcome measure, indicating a familiarization or learning effect, individual changes were calculated from the second baseline value only. Note, the MAL was assessed at the first baseline assessment only, and thus changes in MAL scores were calculated from this single baseline measurement. To account for floor effects, the Nine Hole Peg test scores were measured in pegs placed and removed in 1 min [46].

The resulting data did not deviate significantly from normality for any of the outcome measures at all assessments (Lilliefors test). Thus, a one-tailed *t*-test was used to test for a significant difference in the primary end point between the two training conditions at 1 mo posttherapy. We elected to use a one-tailed test since our primary goal was to determine whether MusicGlove therapy was an improvement over conventional therapy and because any other outcome would result in the same conclusion that current practice should not be modified to include the MusicGlove as a supplement to conventional home therapy [47]. To examine the time effect of therapy, we performed a repeated-measures analysis of variance (ANOVA) of absolute Box and Blocks scores from baseline through 1 mo posttherapy. Follow-up testing of the average changes compared with baseline across all subjects at each assessment was performed using one-tailed *t*-tests with Bonferroni corrections for multiple comparisons at the two time points (i.e., $\alpha = 0.025$) [48].

Secondary end points were analyzed using a repeated-measures ANOVA of the absolute scores from baseline through 1 mo posttherapy. Follow-up tests were performed using two-tailed *t*-tests with Bonferroni corrections to test for significant changes within each group compared with baseline at both assessments (i.e., $\alpha = 0.025$) and one-tailed *t*-tests to test for significant differences between groups at 1 mo posttherapy ($\alpha = 0.05$).

We performed a post hoc analysis of the amount of use data recorded on the MusicGlove laptops, including the crossover data. First, we compared the total number of grips completed during MusicGlove therapy with a target dose of 2,700 total grips, based on a recommended dose of 300 repetitions/h suggested elsewhere [49], multiplied by 9 total hours of prescribed therapy. Then, to compare changes in amount of use as the study progressed, we performed two linear regression analyses for each subject using the total cumulative number of grips completed as the dependent variable and the day of the study as the independent variable for days 1 through 7 (the first week of therapy) and days 8 through 21 (the next two weeks of therapy) for each regression. Here we defined the boundary for a "day" as the grips completed between midnight on one calendar day and midnight on the next. The slopes of the resulting models provided estimates of the number of grips each subject completed per day during the first week of therapy and the next two weeks of therapy. We tested for a significant change in grips completed per day between these two periods across all subjects using a paired, one-tailed *t*-test.

We also analyzed every participant's performance in the MusicGlove game throughout the study (again including the crossover data), measured as the percentage of grips completed successfully out of the total number of grips requested during therapy. We compared each subject's average percentage on the first day of therapy with his or her percentage on the second day to test for a familiarization effect. We then compared each subject's average percentage on the second day of therapy with his or her percentage on the last day of the study to test for long-term improvements. In order to better understand why some participants did not comply with the prescribed regimen, we used a *t*-test to compare the change in percentage from day 1 to day 2 between the participants who did not meet the target dose of 2,700 total grips and those who did.

Finally, we performed an exploratory analysis of the relationship between the number of grips completed with the MusicGlove and the changes in the outcome measures. We did not include the crossover data in this analysis to eliminate any confounding effect of performing conventional therapy before MusicGlove therapy. For each outcome measure, we performed a linear regression analysis with the change in score compared with baseline at 1 mo posttherapy as the dependent variable and the number of grips completed as the independent variable.

RESULTS

Twenty three volunteers were assessed for eligibility in this study (see Consolidated Standards of Reporting Trials diagram, **Figure 2**). Of these, five subjects did not return for the second baseline assessment for unrelated reasons. One subject was excluded from analyses because of absence of follow-up data since the participant did not return for follow-up assessments.

Baseline characteristics for the remaining 17 subjects are presented in **Table 1** and indicate no significant differences between the two treatment groups for any demographic or baseline measures except the Geriatric Depression Scale, which showed that the participants in the MusicGlove group had significantly greater levels of self-perceived depression at study start (p = 0.03, **Table 1**), though average scores in both groups fell short of the cutoff used to indicate major depression. One participant in the MusicGlove group had a Geriatric Depression Scale score of 11, indicating severe depression. Two of the participants in the conventional therapy group had a history of prior stroke, compared with none in the MusicGlove group.

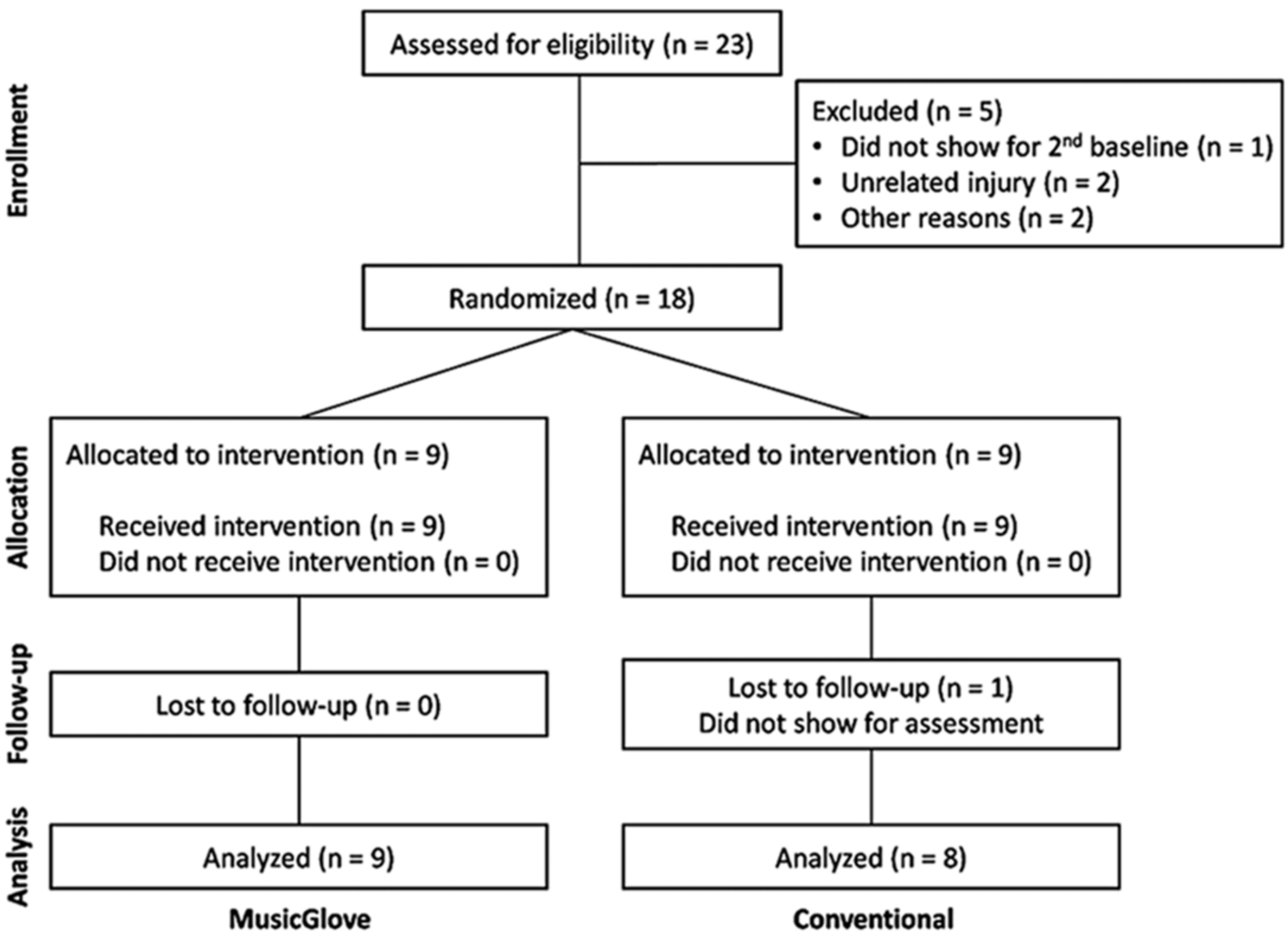

Figure 2.
Consolidated Standards of Reporting Trials flow diagram for study.

No adverse events or safety issues occurred during the course of the study, and the participants reported no increase in pain after either training protocol. Participants in both groups typically required one follow-up call from the research therapist to solve technical issues or clarify the exercise regimen. Both groups reported close adherence to their respective training programs during the 3 wk exercise period, but some participants in the conventional therapy group reported persisting in their exercises after the exercise period ended, against the instructions of the research therapist.

For the Box and Blocks score, a significant difference was found between the two baseline assessments for all study participants, indicating a familiarization effect (increase of 2.2 ± 3.1 blocks, $p = 0.009$). Thus, the change in Box and Blocks score was calculated from the second baseline assessment. No significant differences were found between the two baseline assessments for all secondary end points.

Analysis of the study's primary end point did not indicate a significant difference between groups at 1 mo posttherapy, with the MusicGlove group improving by 2.3 ± 6.2 blocks and the conventional therapy group improving by 4.3 ± 5.0 blocks (**Table 2**). Repeated-measures ANOVA revealed that the main effect of time was significant on change in Box and Blocks score ($F(2,30) = 3.85$, $p = 0.03$), but the group-time interaction effect was not significant ($p = 0.23$). Follow-up analysis revealed a significant change compared with baseline of 3.2 ± 5.6 blocks averaged across all subjects at 1 mo posttherapy (one-tailed *t*-test, $p = 0.02$; **Figure 3**).

Repeated-measures ANOVA of the secondary end points revealed that the main effect of time was significant on change in MAL QOM score ($F(2,30) = 6.98$, $p = 0.003$) and MAL AOU score ($F(2,30) = 9.45$, $p < 0.001$). There was also a significant group-time interaction effect on change in MAL QOM score ($F(2,30) = 3.96$, $p = 0.03$) and a marginally significant group-time interaction effect on change in MAL AOU score ($F(2,30) = 2.44$, $p = 0.10$). Repeated-measures ANOVA did not reveal any significant effects of treatment on Nine Hole Peg test or ARAT scores.

Follow-up testing revealed participants in the MusicGlove group had significant changes compared with baseline in MAL QOM and AOU scores both immediately posttherapy (two-tailed *t*-test, $p = 0.03$ and $p = 0.01$,

Table 1.
Participant demographics and baseline measures.

Measure	Conventional	MusicGlove	*p*-Value
Demographics			
Participants (*n*)	8	9	—
Mean Age, yr (range)	59 (35–74)	60 (45–74)	0.71
Sex (*n*)			0.63
Female	3	4	
Male	5	5	
Time Poststroke, yr (mean ± SD)	3.17 ± 1.66	5.33 ± 4.14	0.21
Baseline Characteristics (mean ± SD)			
Geriatric Depression Scale (>10 indicates depression)	1.8 ± 1.4	4.6 ± 2.9	0.03
Upper Extremity Fugl-Meyer Score (max: 66)*	56.4 ± 6.3	53.8 ± 8.9	0.53
NIH Stroke Scale Score (normal: 0)	1.8 ± 1.7	1.4 ± 1.2	0.69
Modified Ashworth Spasticity Scale, Wrist (normal: 0)	1.3 ± 1.0	1.9 ± 1.2	0.28
Baseline Outcome Measures (mean ± SD)†			
Box and Blocks Test (blocks/min)*	32.6 ± 10.3	33.0 ± 10.6	0.85
Motor Activity Log (max: 5)*			
Quality of Movement	2.54 ± 1.09	2.31 ± 0.74	0.64
Amount of Use	2.58 ± 0.90	2.33 ± 0.83	0.58
Nine Hole Peg Test (pegs/min)*	18.3 ± 13.7	15.6 ± 10.0	0.39
ARAT Score (max: 57)*	51 ± 9	44 ± 17	0.42

*For these scales, higher score is better.
†Values reported are from first baseline assessment.
ARAT = Action Research Arm Test, max = maximum, NIH = National Institutes of Health, SD = standard deviation.

Table 2.
Change in outcome measures compared with baseline at 1 mo posttreatment. Unless otherwise indicated, values are given as mean ± standard deviation.

Outcome	MusicGlove (n = 9)	Conventional (n = 8)	Mean Difference (95% CI)	p-Value (one-tailed)
Box and Blocks Test	2.3 ± 6.2	4.3 ± 5.0	–1.9 (–6.7 to 2.9)	0.25
Motor Activity Log				
Quality of Movement	0.82 ± 0.48*	0.09 ± 0.58	0.72 (0.27 to 1.17)	0.007
Amount of Use	0.86 ± 0.64*	0.26 ± 0.69	0.60 (0.04 to 1.16)	0.04
Nine Hole Peg Test	1.3 ± 6.9	–0.2 ± 6.0	1.5 (–4.1 to 7.1)	0.33
Action Research Arm Test	0.7 ± 2.3	–0.6 ± 2.9	1.2 (–1.0 to 3.4)	0.29

*Significantly difference than baseline (two-tailed t-test, $p < 0.03$).
CI = confidence interval.

respectively) and at 1 mo posttherapy (two-tailed t-test, $p < 0.001$ and $p = 0.004$, respectively; see **Figure 3**). No significant changes compared with baseline were found for either outcome measure after conventional therapy. Subjects in the MusicGlove group had significantly greater improvements in both MAL QOM score and AOU score than subjects in the conventional therapy group at 1 mo posttherapy (mean differences of 0.72 and 0.60 points, one-tailed t-test, $p = 0.007$ and $p = 0.04$, respectively; **Table 2**).

Subjects were asked to fill out an activity log to record the amount of time they spent exercising during the 3 wk training period. Seven of the nine participants from the MusicGlove group and four of the eight participants from the control group filled out the activity log as requested. Participants in the MusicGlove group reported exercising for an average of 1.9 h total more than the control group during the training phase (10 h vs 8.1 h, respectively), but this difference was not significant.

The total number of grips completed with the MusicGlove during the exercise period was recorded for each participant on the laptops provided. Data were not recovered for two of the participants due to technical errors. Of the remaining 15 participants (8 from the original MusicGlove group, 7 from the crossover group), 11 completed the target dose of 2,700 grips. Four individuals completed over 10,000 grips, with two of these completing over 30,000 grips (**Figure 4(a)**).

When we examined the time course of practice, we found that the cumulative number of grips completed each day was well represented by two lines, with an average R^2 value for a line fit across all subjects of 0.82 ± 0.14 during the first week of therapy and an average R^2 of 0.86 ± 0.16 for a line fit to the data during the next two weeks. Using the slopes from these linear models, we estimated that the participants completed an average of 213 ± 301 grips per day during the first week of therapy and 466 ± 641 grips per day during the next two weeks of therapy, a significant difference ($p = 0.04$; **Figure 4(b)**). That is, the participants intensified their use of the MusicGlove after the first week of exposure.

We also examined the participants' performance in the MusicGlove game throughout the study, measured as the percentage of notes hit correctly. Performance increased throughout the study, with a significant increase of 11 ± 13 percent from day 1 to day 2 of therapy (t-test, $p = 0.01$) and a nonsignificant increase from day 2 to the end of the study of 6 ± 15 percent.

Of the four participants who did not complete the target dose of 2,700 grips, three had an average performance of 15 percent or less (i.e., for every 100 notes presented, they successfully completed only 15 or less). Of the 11 participants who completed at least 2,700 grips, all 11 had an average performance of 22 percent or more, with a group mean of 53 ± 15 percent. Also, the group that completed at least 2,700 grips during therapy (n = 11) had an increase in performance of 14 ± 14 percent from day 1 to day 2 of therapy, while the group that did not complete the target dose (n = 4) had a decrease in performance of 1 ± 2 percent over the same time span, a significant difference ($p = 0.008$).

In an exploratory analysis (n = 8), we found a significant linear relationship between the number of grips completed with the MusicGlove and the change in MAL AOU score at 1 mo posttherapy, with a slope of 0.05 points for every 1,000 grips completed with the MusicGlove ($R^2 = 0.61$, $p = 0.02$). No other outcome measures were significantly related to number of grips completed.

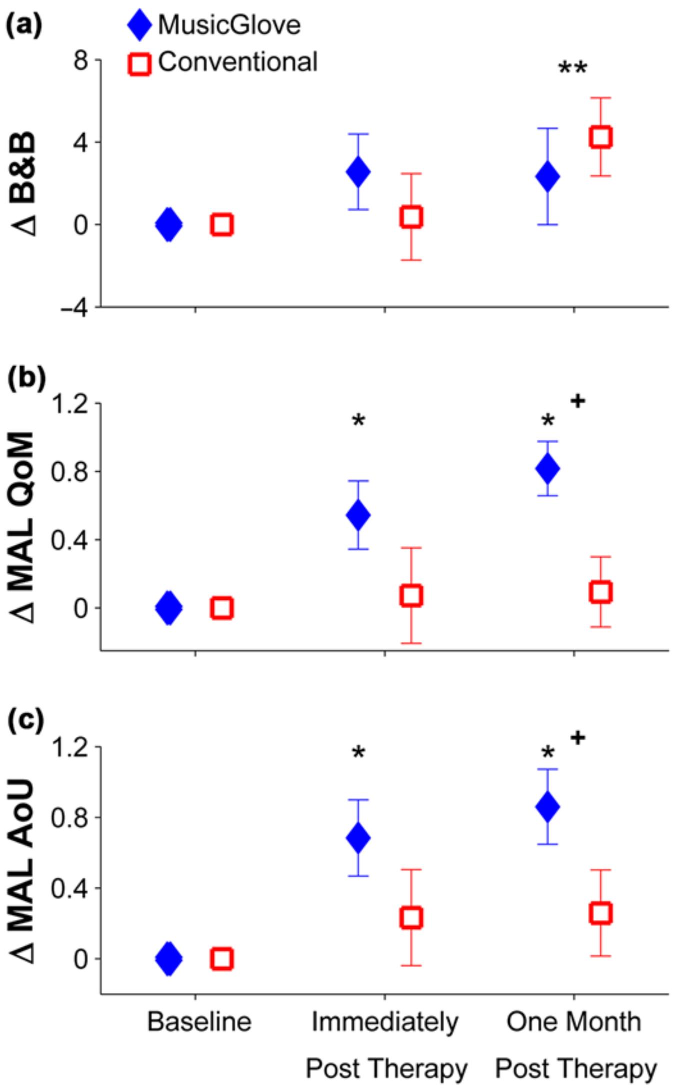

Figure 3.
(a) Longitudinal changes in Box and Blocks test (B&B), **(b)** Motor Activity Log (MAL) Quality of Movement (QoM), and **(c)** MAL Amount of Use (AoU) throughout experiment. MusicGlove group (solid blue diamonds) had significantly greater improvements than conventional therapy group (open red squares) in both MAL scores 1 mo after therapy. Error bars indicate ±1 standard error. *Significant within-group changes compared with baseline (two-tailed t-test, $p < 0.03$). **Significant changes across both groups compared with baseline (one-tailed t-test, $p < 0.03$). +Significant differences between groups at 1 mo posttherapy (one-tailed t-test, $p < 0.05$).

Finally, we performed two more exploratory analyses. First, we noticed that one of the MusicGlove participants had a decrease in Box and Blocks score from baseline of 10 blocks at 1 mo posttherapy and a decrease of only 2 blocks immediately after therapy. This was a large change relative to all other participants (greater than two standard deviations away from the group mean), and thus we speculated that this decrease may have been due to poor motivation on that particular day. When we removed this participant from the analysis, the change in Box and Blocks score compared with baseline for the MusicGlove group increased to 3.9 ± 1.7 blocks at 1 mo posttherapy. Second, for all end points, we also analyzed the combined data from the MusicGlove group and the data from the crossover period for the conventional therapy group, in which they also received MusicGlove therapy (resulting in an $n = 17$ for the MusicGlove group). Here, the changes in outcome measures for the crossover group were calculated from the "baseline" of the 1 mo posttherapy assessment after conventional therapy. In this analysis, the MusicGlove group had a significantly greater change in ARAT score than the conventional therapy group ($n = 8$) at 1 mo posttherapy (mean difference of 2.4 points, one-tailed t-test, $p = 0.046$). Thus, both of these exploratory analyses supported positive effects of MusicGlove training, although the first relied on an ad hoc outlier removal and the second combined change scores without a prior history of participation in conventional training with change scores that were dependent on a prior history of participation in conventional training.

DISCUSSION

Increased Functional Use of Hand After MusicGlove Therapy

Notably, some of the participants in the conventional therapy group did not adhere to the study protocol and continued exercising after the exercise period. This may explain why the conventional therapy group had a substantial increase in Box and Blocks score at 1 mo posttherapy after a relatively small increase immediately posttherapy (**Figure 3**). Yet, despite the fact that there was a significant increase in Box and Blocks score across both the MusicGlove and conventional therapy groups at 1 mo posttherapy, only the MusicGlove group converted this improvement in gripping function into increased self-reported functional use of the hand as measured by the MAL scores.

One possible explanation for this increased functional use of the hand after MusicGlove therapy is that thumb

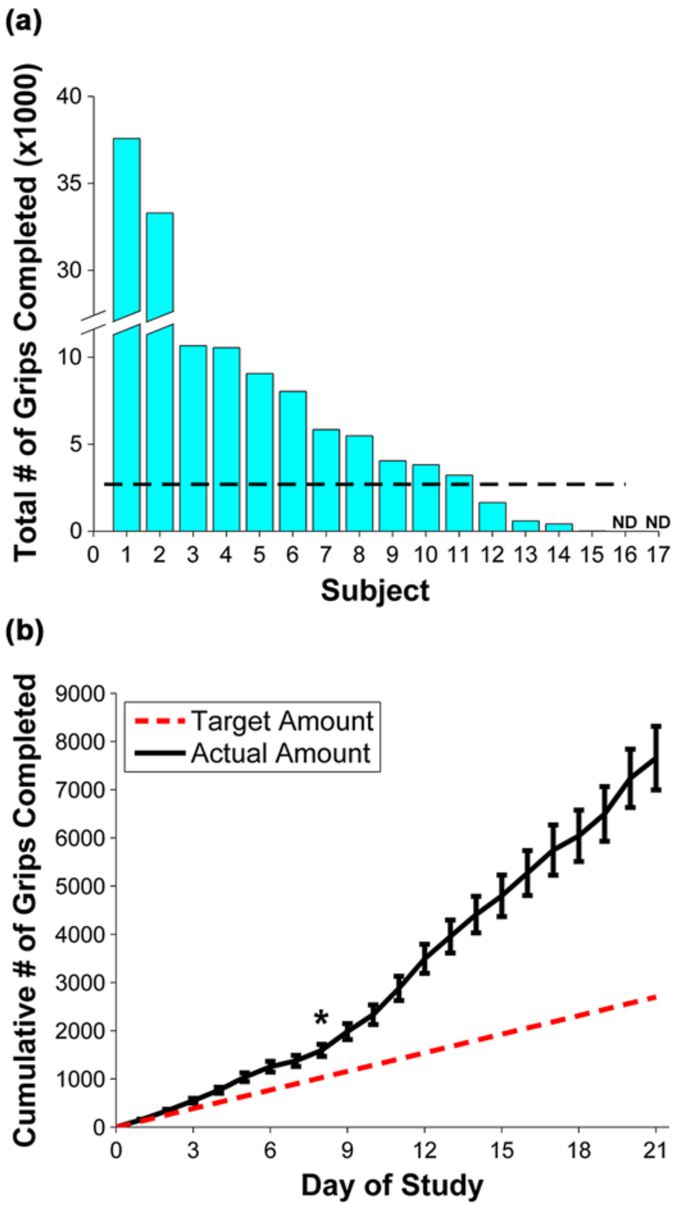

Figure 4.
(a) Number of grips completed with MusicGlove by each study participant, including crossover data. Note break in *y*-axis from 12,000 to 27,000 grips, which was inserted for readability. Dashed line represents target dose of 2,700 total grips. **(b)** Mean cumulative number of grips completed as function of day in study for all study participants, including crossover data. Dashed line represents expected progression of cumulative number of grips if subjects practiced 300 repetitions/h, 3 h/wk, for 3 wk. Average number of grips completed per day across all subjects increased significantly from first week of therapy to next 2 wk of therapy (p = 0.04). *Transition point (i.e., day 8). Error bars show ±1 standard error. ND = data not available for participants.

opposition is critical for functional use of the hand, and the MusicGlove is more effective at promoting intensive training of thumb opposition than conventional therapy. Another more general possibility is that functional use of the hand requires several fundamental movement patterns of the fingers and thumb and that the MusicGlove is effective at training these patterns. Indeed, a study that used principal component decomposition to analyze the movement patterns associated with functional use of the hand found that >90 percent of the variance in hand kinematics could be explained by nine finger-thumb movement patterns similar to ones trained by the MusicGlove [50]. In this framework, practicing a key movement component that is used in a range of daily tasks may be more efficient at inducing functional recovery than practicing the individual tasks themselves [51–53], a hypothesis one could call "component-specific training" in order to contrast it with the widely advocated approach of "task-specific training." A third possibility is that practice with the MusicGlove simply made the participants pay more attention to their hand, and thus they were more inclined to report an increased use of it in daily tasks.

Comparison with Previous Hand Therapy Studies

Our previous clinic-based study of the MusicGlove [27–28] included participants with a chronic stroke of similar duration and similar levels of initial hand impairment as the current study. However, in that study, subjects trained for 2 wk in six 1 h sessions with the MusicGlove under continuous supervision. The change in Box and Blocks score was 3.2 blocks after 6 h of clinical therapy versus 2.3 blocks after 9 h of home-based therapy in the current study. Thus, the gains achievable at home were comparable to those achieved in the clinic, though there is a mild indication that clinic-based therapy is more efficient at improving gripping function.

The largest trial of hand therapy reported to date is the EXCITE trial, which used large amounts of graded, task-oriented exercises [54–55]. Specifically, participants in the EXCITE trial received a total of 60 h of therapy for up to 6 h/d, 5 d/wk, for 2 wk, during which they were prevented from using their nonimpaired limb. In the present study, the functional gains following MusicGlove use were 0.82 for MAL QOM and 0.86 for MAL AOU. Following the EXCITE trial, the functional gains were 1.12 for MAL QOM and 1.07 for MAL AOU. This finding that participants who used the MusicGlove achieved about 75 to 80 percent of the benefit reported on the

MAL for the EXCITE trial despite less training time, absence of a constraint on their nonimpaired hand, and use of home therapy rather than therapist-supervised training is notable.

Comparing the outcomes of the present study with other home-based hand therapy trials is difficult because of variations in study protocol, amount of therapist guidance provided, and outcome measures [14,17–23]. However, the improvements in Box and Blocks score seen here are similar to the gains observed in a prior home-based telerehabilitation study with chronic stroke subjects that incorporated virtual line-tracking with a finger goniometer, which reported changes of 2.0 and 4.9 blocks in the two study groups [16]. That study included five video calls between the therapist and the patient over a 10 d training period, while the present study used less interaction.

Influence of Motivating Factors on Dose of Exercise and Long-Term Outcomes

There is growing consensus that individuals typically perform far too few exercise repetitions to maximize recovery after stroke [7,49,56]. Indeed, our exploratory analysis of the relationship between number of grips completed and outcomes suggested that, at least in terms of increasing self-reported functional use of the hand, there is a positive correlation between the dose of therapy and outcomes. However, the slope of that correlation was small, indicating that thousands of additional exercise repetitions are required in order to promote increased functional use.

As mentioned in the "Methods" section, a recent study suggested 300 repetitions in a 1 h therapy session was an appropriate target [49]; this is an order of magnitude more than the number of repetitions typically performed in guided therapy sessions [7]. Of the 15 participants in the present study whose MusicGlove usage data were collected successfully, 11 exceeded this target. Of the four participants who did not, three had very low levels of performance in the MusicGlove game, in terms of percentage of notes successfully hit, suggesting that the therapy was difficult for them. Further, none of these four participants improved their performance from day 1 to day 2 of therapy, which could have reduced their motivation to continue. This is in line with other studies that have shown high levels of difficulty or lack of improvement in a task can reduce motivation to persist [57–59]. Based on the results of this study, a minimum average performance of 20 percent in the MusicGlove game may be an important factor for maintaining motivation during home therapy with the device.

Interestingly, instead of observing a novelty effect in which the participants initially used the MusicGlove more frequently and then tapered off their use, we instead observed that the participants significantly increased their use of the device after the first week of therapy, completing on average over 200 additional grips per day during the next 2 wk. Some of this increase may have been due to increased performance in the game (i.e., the participants completed a higher percentage of the grips that were requested during a given song, resulting in more grips per day). However, performance data from the laptops showed an average improvement of only 6 percent from the second to the final day of therapy, which would have resulted in an increase of only about 30 additional grips per day if the amount of practice time had remained the same. Thus, a better explanation of the increase in grips completed per day is that the participants became more interested and motivated to use the MusicGlove after their initial exposure to it.

Indeed, the use of motivating factors such as music and video games during therapy may be an important approach to improve the long-term outcomes of a rehabilitation program. Music has been shown to encourage movement via tightly coupled interaction between the auditory and motor cortices, which may improve motor recovery [26,60–61]. Also, the use of music during therapy may enhance neural reorganization, thus increasing functional outcomes from the therapy [25,62–69]. The use of video games not only creates an immersive exercise experience but can also encourage a high number of repetitions, create an appropriate level of challenge, reward progress, and provide feedback on improvements over time. The MusicGlove includes each of these features, all of which have been linked to improved long-term outcomes of therapy [58,70–73] and likely contributed to the significant improvements in motor function after MusicGlove therapy in the present study.

Of particular note is that the participants in the MusicGlove group had significantly higher levels of self-reported depression on the Geriatric Depression Scale than the conventional therapy group at baseline (i.e., they were more likely to respond negatively to questions pertaining to their quality of life). This may have been expected to limit functional improvements in this group since depressive symptoms have been shown to reduce outcomes from rehabilitation after stroke [74] and are correlated with an inability to carry out many activities of daily living [75]. Indeed, one participant did report poor adherence to the study protocol because of severe depression. However, for the rest of the participants, this was not the case. We did not reassess the participants' scores on the Geriatric Depression Scale at the 1 mo follow-up, but future studies should assess whether exercising with the MusicGlove can improve psychological well-being. This may in turn promote increased functional use of the hand, such as we observed here.

Limitations and Future Directions

Limitations of this study include a small sample size, the conventional therapy group's poor adherence to the study protocol by continuing to exercise after the 3 wk training period, the lack of an accurate measure of the number of exercise repetitions the participants in the conventional therapy group performed during the experiment, subject dropout, and incomplete data collection on two of the MusicGlove laptops because of technical errors. Common technical difficulties with the MusicGlove included an inability to double-click the desktop icon that opened the MusicGlove application on the laptop, difficulties using a tracking pad to control the laptop cursor, difficulty properly exiting the MusicGlove application, and difficulty turning the computer on and off. There were few technical issues with the MusicGlove hardware itself.

Future research should explore the use of MusicGlove therapy in individuals with subacute stroke and other populations that exhibit hand impairment, such as those with traumatic brain injury and spinal cord injury. Other studies could also examine which motivating factors (e.g., music or video games) are most effective for facilitating large amounts of movement practice and improving long-term functional outcomes and the mechanisms by which these factors influence self-report of functional use of the hand. Finally, the ability of the MusicGlove to accurately record the number of movement repetitions performed during exercise makes it well-suited for use in a study that explores the relationship between dose and therapeutic outcomes. Further studies could expand on the small exploratory analysis we presented here by examining this relationship across a larger sample size and under a more closely controlled therapeutic regimen.

CONCLUSIONS

The results of this study confirmed that the MusicGlove is viable and effective for home therapy, and it motivated users to complete a high number of therapeutic gripping movements. We did not observe a significant difference between MusicGlove therapy and conventional therapy in the primary end point, but we did observe a significant difference in favor of the MusicGlove in two of the secondary end points (MAL AOU and QOM).

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Administrative, technical, or material support: E. Chang, X. Zhao.
Study supervision: N. Friedman, D. J. Reinkensmeyer, R. Augsburger.

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REFERENCES

1. Dobkin BH. Neurologic rehabilitation. Philadelphia (PA): F. A. Davis; 1996.
2. Sawaki L. Use-dependent plasticity of the human motor cortex in health and disease. IEEE Eng Med Biol Mag. 2005;24(1):36–39. [PMID:15709534] http://dx.doi.org/10.1109/MEMB.2005.1384098
3. Ada L, Dorsch S, Canning CG. Strengthening interventions increase strength and improve activity after stroke: A systematic review. Aust J Physiother. 2006;52(4):241–48. [PMID:17132118] http://dx.doi.org/10.1016/S0004-9514(06)70003-4
4. van der Lee JH, Snels IA, Beckerman H, Lankhorst GJ, Wagenaar RC, Bouter LM. Exercise therapy for arm function in stroke patients: A systematic review of randomized controlled trials. Clin Rehabil. 2001;15(1):20–31. [PMID:11237158] http://dx.doi.org/10.1191/026921501677557755
5. Kloosterman MG, Snoek GJ, Jannink MJ. Systematic review of the effects of exercise therapy on the upper extremity of patients with spinal-cord injury. Spinal Cord. 2009;47(3):196–203. [PMID:18825160] http://dx.doi.org/10.1038/sc.2008.113
6. Nudo RJ. Postinfarct cortical plasticity and behavioral recovery. Stroke. 2007;38(2 Suppl):840–45. [PMID:17261749] http://dx.doi.org/10.1161/01.STR.0000247943.12887.d2
7. Lang CE, Macdonald JR, Reisman DS, Boyd L, Jacobson Kimberley T, Schindler-Ivens SM, Hornby TG, Ross SA, Scheets PL. Observation of amounts of movement practice provided during stroke rehabilitation. Arch Phys Med Rehabil. 2009;90(10):1692–98. [PMID:19801058] http://dx.doi.org/10.1016/j.apmr.2009.04.005
8. Byl NN, Pitsch EA, Abrams GM. Functional outcomes can vary by dose: Learning-based sensorimotor training for patients stable poststroke. Neurorehabil Neural Repair. 2008;22(5):494–504. [PMID:18780884] http://dx.doi.org/10.1177/1545968308317431
9. Cox KL, Burke V, Gorely TJ, Beilin LJ, Puddey IB. Controlled comparison of retention and adherence in home- vs center-initiated exercise interventions in women ages 40-65 years: The S.W.E.A.T. Study (Sedentary Women Exercise Adherence Trial). Prev Med. 2003;36(1):17–29. [PMID:12473421] http://dx.doi.org/10.1006/pmed.2002.1134
10. Rejeski WJ, Brawley LR, Ettinger W, Morgan T, Thompson C. Compliance to exercise therapy in older participants with knee osteoarthritis: Implications for treating disability. Med Sci Sports Exerc. 1997;29(8):977–85. [PMID:9268953] http://dx.doi.org/10.1097/00005768-199708000-00001
11. Sluijs EM, Kok GJ, van der Zee J. Correlates of exercise compliance in physical therapy. Phys Ther. 1993;73(11): 771–82, discussion 783–86. [PMID:8234458]
12. Turton A, Fraser C. The use of home therapy programmes for improving recovery of the upper limb following stroke. Br J Occup Ther. 1990;53(11):457–62. http://dx.doi.org/10.1177/030802269005301104
13. Jurkiewicz MT, Marzolini S, Oh P. Adherence to a home-based exercise program for individuals after stroke. Top Stroke Rehabil. 2011;18(3):277–84. [PMID:21642065] http://dx.doi.org/10.1310/tsr1803-277
14. Barzel A, Liepert J, Haevernick K, Eisele M, Ketels G, Rijntjes M, van den Bussche H. Comparison of two types of Constraint-Induced Movement Therapy in chronic stroke patients: A pilot study. Restor Neurol Neurosci. 2009;27(6):673–80. [PMID:20042791]
15. Barzel A, Ketels G, Stark A, Tetzlaff B, Daubman A, Wegscheider K, van den Bussche H, Scherer M. Home-based constraint-induced movement therapy for patients with upper limb dysfunction after stroke (HOMECIMT): A cluster-randomized, controlled trial. Lancet Neurol. 2015; 14(9):893–902. [PMID:26231624] http://dx.doi.org/10.1016/S1474-4422(15)00147-7
16. Carey JR, Durfee WK, Bhatt E, Nagpal A, Weinstein SA, Anderson KM, Lewis SM. Comparison of finger tracking versus simple movement training via telerehabilitation to alter hand function and cortical reorganization after stroke. Neurorehabil Neural Repair. 2007;21(3):216–32. [PMID:17351083] http://dx.doi.org/10.1177/1545968306292381
17. Laver KE, Schoene D, Crotty M, George S, Lannin NA, Sherrington C. Telerehabilitation services for stroke. Cochrane Database Syst Rev. 2013;12:CD010255. [PMID:24338496]
18. Hara Y, Ogawa S, Tsujiuchi K, Muraoka Y. A home-based rehabilitation program for the hemiplegic upper extremity by power-assisted functional electrical stimulation. Disabil Rehabil. 2008;30(4):296–304. [PMID:17852312] http://dx.doi.org/10.1080/09638280701265539
19. Donoso Brown EV, McCoy SW, Fechko AS, Price R, Gilbertson T, Moritz CT. Preliminary investigation of an electromyography-controlled video game as a home program for persons in the chronic phase of stroke recovery. Arch Phys Med Rehabil. 2014;95(8):1461–69. [PMID:24657112] http://dx.doi.org/10.1016/j.apmr.2014.02.025
20. King M, Hijmans JM, Sampson M, Satherley J, Hale L. Home-based stroke rehabilitation using computer gaming. N Z J Physiother. 2012;40(3):128–34.
21. Slijper A, Svensson KE, Backlund P, Engström H, Sunnerhagen KS. Computer game-based upper extremity training in the home environment in stroke persons: A single subject design. J Neuroeng Rehabil. 2014;11:35.

[PMID:24625289]
http://dx.doi.org/10.1186/1743-0003-11-35
22. Villeneuve M, Lamontagne A. Playing piano can improve upper extremity function after stroke: case studies. Stroke Res Treat. 2013;2013:159105. [PMID:23533954] http://dx.doi.org/10.1155/2013/159105
23. Coupar F, Pollock A, Legg LA, Sackley C, van Vliet P. Home-based therapy programmes for upper limb functional recovery following stroke. Cochrane Database Syst Rev. 2012;5:CD006755. [PMID:22592715]
24. Hijmans JM, Hale LA, Satherley JA, McMillan NJ, King MJ. Bilateral upper-limb rehabilitation after stroke using a movement-based game controller. J Rehabil Res Dev. 2011;48(8):1005–13. [PMID:22068375] http://dx.doi.org/10.1682/JRRD.2010.06.0109
25. Safranek BR. The use of music therapy in stroke rehabilitation. Music Ther. 2011;1:1–13.
26. Yoo J. The role of therapeutic instrumental music performance in hemiparetic arm rehabilitation. Music Ther Perspect. 2009; 27(1):16–24. http://dx.doi.org/10.1093/mtp/27.1.16
27. Friedman N, Chan V, Reinkensmeyer AN, Beroukhim A, Zambrano GJ, Bachman M, Reinkensmeyer DJ. Retraining and assessing hand movement after stroke using the MusicGlove: Comparison with conventional hand therapy and isometric grip training. J Neuroeng Rehabil. 2014;11:76. [PMID:24885076] http://dx.doi.org/10.1186/1743-0003-11-76
28. Friedman N, Chan V, Zondervan D, Bachman M, Reinkensmeyer DJ. MusicGlove: motivating and quantifying hand movement rehabilitation by using functional grips to play music. Conf Proc IEEE Eng Med Biol Soc. 2011; 2011:2359–63. [PMID:22254815] http://dx.doi.org/10.1109/IEMBS.2011.6090659
29. Mathiowetz V, Volland G, Kashman N, Weber K. Adult norms for the Box and Block Test of manual dexterity. Am J Occup Ther. 1985;39(6):386–91. [PMID:3160243] http://dx.doi.org/10.5014/ajot.39.6.386
30. Platz T, Pinkowski C, van Wijck F, Kim I-H, di Bella P, Johnson G. Reliability and validity of arm function assessment with standardized guidelines for the Fugl-Meyer Test, Action Research Arm Test and Box and Block Test: A multicentre study. Clin Rehabil. 2005;19(4):404–11. [PMID:15929509] http://dx.doi.org/10.1191/0269215505cr832oa
31. Uswatte G, Taub E, Morris D, Vignolo M, McCulloch K. Reliability and validity of the upper-extremity Motor Activity Log-14 for measuring real-world arm use. Stroke. 2005;36(11):2493–96. [PMID:16224078] http://dx.doi.org/10.1161/01.STR.0000185928.90848.2e
32. Uswatte G, Taub E, Morris D, Light K, Thompson PA. The Motor Activity Log-28: Assessing daily use of the hemiparetic arm after stroke. Neurology. 2006;67(7):1189–94. [PMID:17030751] http://dx.doi.org/10.1212/01.wnl.0000238164.90657.c2
33. Oxford Grice K, Vogel KA, Le V, Mitchell A, Muniz S, Vollmer MA. Adult norms for a commercially available Nine Hole Peg Test for finger dexterity. Am J Occup Ther. 2003;57(5):570–73. [PMID:14527120] http://dx.doi.org/10.5014/ajot.57.5.570
34. Yozbatiran N, Der-Yeghiaian L, Cramer SC. A standardized approach to performing the action research arm test. Neurorehabil Neural Repair. 2008;22(1):78–90. [PMID:17704352] http://dx.doi.org/10.1177/1545968307305353
35. Yesavage JA, Brink TL, Rose TL, Lum O, Huang V, Adey M, Leirer VO; Yesavage. Development and validation of a geriatric depression screening scale: A preliminary report. J Psychiatr Res. 1982–1983;17(1):37–49. [PMID:7183759] http://dx.doi.org/10.1016/0022-3956(82)90033-4
36. Gladstone DJ, Danells CJ, Black SE. The Fugl-Meyer assessment of motor recovery after stroke: A critical review of its measurement properties. Neurorehabil Neural Repair. 2002;16(3):232–40. [PMID:12234086] http://dx.doi.org/10.1177/154596802401105171
37. Lyden P, Brott T, Tilley B, Welch KM, Mascha EJ, Levine S, Haley EC, Grotta J, Marler J; NINDS TPA Stroke Study Group. Improved reliability of the NIH Stroke Scale using video training. Stroke. 1994;25(11):2220–26. [PMID:7974549] http://dx.doi.org/10.1161/01.STR.25.11.2220
38. Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. Phys Ther. 1987; 67(2):206–7. [PMID:3809245]
39. Hummel F, Celnik P, Giraux P, Floel A, Wu W-H, Gerloff C, Cohen LG. Effects of non-invasive cortical stimulation on skilled motor function in chronic stroke. Brain. 2005; 128(Pt 3):490–99. [PMID:15634731] http://dx.doi.org/10.1093/brain/awh369
40. Chen H-M, Chen CC, Hsueh I-P, Huang S-L, Hsieh C-L. Test-retest reproducibility and smallest real difference of 5 hand function tests in patients with stroke. Neurorehabil Neural Repair. 2009;23(5):435–40. [PMID:19261767] http://dx.doi.org/10.1177/1545968308331146
41. Meinert CL, Tonascia S. Clinical trials: Design, conduct, and analysis. New York (NY): Oxford University Press; 1986.
42. Housman SJ, Scott KM, Reinkensmeyer DJ. A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. Neurorehabil Neural Repair. 2009;23(5):505–14. [PMID:19237734] http://dx.doi.org/10.1177/1545968308331148
43. Takahashi CD, Der-Yeghiaian L, Le V, Motiwala RR, Cramer SC. Robot-based hand motor therapy after stroke.

Brain. 2008 Feb;131(Pt 2):425-437. PMID:18156154 http://dx.doi.org/10.1093/brain/awm311

44. Feys HM, De Weerdt WJ, Selz BE, Cox Steck GA, Spichiger R, Vereeck LE, Putman KD, Van Hoydonck GA. Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke: A single-blind, randomized, controlled multicenter trial. Stroke. 1998; 29(4):785–92. [PMID:9550512] http://dx.doi.org/10.1161/01.STR.29.4.785
45. Kwakkel G, Wagenaar RC, Twisk JW, Lankhorst GJ, Koetsier JC. Intensity of leg and arm training after primary middle-cerebral-artery stroke: A randomised trial. Lancet. 1999; 354(9174):191–96. [PMID:10421300] http://dx.doi.org/10.1016/S0140-6736(98)09477-X
46. Brunner IC, Skouen JS, Strand LI. Recovery of upper extremity motor function post stroke with regard to eligibility for constraint-induced movement therapy. Top Stroke Rehabil. 2011;18(3):248–57. [PMID:21642062] http://dx.doi.org/10.1310/tsr1803-248
47. Ruxton GD, Neuhäuser M. When should we use one-tailed hypothesis testing? Methods Ecol Evol. 2010;1(2):114–17. http://dx.doi.org/10.1111/j.2041-210X.2010.00014.x
48. Holm S. A simple sequentially rejective multiple test procedure. Scand J Stat. 1979;6(2):65–70.
49. Birkenmeier RL, Prager EM, Lang CE. Translating animal doses of task-specific training to people with chronic stroke in 1-hour therapy sessions: A proof-of-concept study. Neurorehabil Neural Repair. 2010;24(7):620–35. [PMID:20424192] http://dx.doi.org/10.1177/1545968310361957
50. Thakur PH, Bastian AJ, Hsiao SS. Multidigit movement synergies of the human hand in an unconstrained haptic exploration task. J Neurosci. 2008;28(6):1271–81. [PMID:18256247] http://dx.doi.org/10.1523/JNEUROSCI.4512-07.2008
51. Klein J, Spencer SJ, Reinkensmeyer DJ. Breaking it down is better: Haptic decomposition of complex movements aids in robot-assisted motor learning. IEEE Trans Neural Syst Rehabil Eng. 2012;20(3):268–75. [PMID:22531825] http://dx.doi.org/10.1109/TNSRE.2012.2195202
52. Milot M-H, Spencer SJ, Chan V, Allington JP, Klein J, Chou C, Bobrow JE, Cramer SC, Reinkensmeyer DJ. A crossover pilot study evaluating the functional outcomes of two different types of robotic movement training in chronic stroke survivors using the arm exoskeleton BONES. J Neuroeng Rehabil. 2013;10:112. [PMID:24354476] http://dx.doi.org/10.1186/1743-0003-10-112
53. Zondervan DK, Augsburger R, Bodenhoefer B, Friedman N, Reinkensmeyer DJ, Cramer SC. Machine-based, self-guided home therapy for individuals with severe arm impairment after stroke: A randomized controlled trial. Neurorehabil Neural Repair. 2015;29(5):395–406. [PMID:25273359] http://dx.doi.org/10.1177/1545968314550368
54. Wolf SL, Winstein CJ, Miller JP, Thompson PA, Taub E, Uswatte G, Morris D, Blanton S, Nichols-Larsen D, Clark PC. Retention of upper limb function in stroke survivors who have received constraint-induced movement therapy: The EXCITE randomised trial. Lancet Neurol. 2008;7(1): 33–40. [PMID:18077218] http://dx.doi.org/10.1016/S1474-4422(07)70294-6
55. Cramer SC. The EXCITE trial: a major step forward for restorative therapies in stroke. Stroke. 2007;38(7):2204–5. [PMID:17540965]
56. Plautz EJ, Milliken GW, Nudo RJ. Effects of repetitive motor training on movement representations in adult squirrel monkeys: Role of use versus learning. Neurobiol Learn Mem. 2000;74(1):27–55. [PMID:10873519] http://dx.doi.org/10.1006/nlme.1999.3934
57. Duarte JE, Gebrekristos B, Perez S, Rowe JB, Sharp K, Reinkensmeyer DJ. Effort, performance, and motivation: Insights from robot-assisted training of human golf putting and rat grip strength. IEEE Int Conf Rehabil Robot. 2013; 2013:6650461. [PMID:24187278] http://dx.doi.org/10.1109/ICORR.2013.6650461
58. Guadagnoli MA, Lee TD. Challenge point: A framework for conceptualizing the effects of various practice conditions in motor learning. J Mot Behav. 2004;36(2):212–24. [PMID:15130871] http://dx.doi.org/10.3200/JMBR.36.2.212-224
59. Reinkensmeyer DJ, Housman SJ. “If I can’t do it once, why do it a hundred times?”: Connecting volition to movement success in a virtual environment motivates people to exercise the arm after stroke. Proceedings of the Virtual Rehabilitation Conference; 2007 Sep 27–29; Venice, Italy.
60. Bangert M, Peschel T, Schlaug G, Rotte M, Drescher D, Hinrichs H, Heinze HJ, Altenmüller E. Shared networks for auditory and motor processing in professional pianists: Evidence from fMRI conjunction. Neuroimage. 2006; 30(3):917–26. [PMID:16380270] http://dx.doi.org/10.1016/j.neuroimage.2005.10.044
61. Fujioka T, Ween JE, Jamali S, Stuss DT, Ross B. Changes in neuromagnetic beta-band oscillation after music-supported stroke rehabilitation. Ann N Y Acad Sci. 2012;1252(1): 294–304. [PMID:22524371] http://dx.doi.org/10.1111/j.1749-6632.2011.06436.x
62. Gordon WA, Hibbard MR. Critical issues in cognitive remediation. Neuropsychology. 1992;6(4):361–70. http://dx.doi.org/10.1037/0894-4105.6.4.361
63. Särkämö T, Tervaniemi M, Laitinen S, Forsblom A, Soinila S, Mikkonen M, Autti T, Silvennoinen HM, Erkkilä J, Laine M, Peretz I, Hietanen M. Music listening enhances cognitive recovery and mood after middle cerebral artery

stroke. Brain. 2008;131(Pt 3):866–76. [PMID:18287122] http://dx.doi.org/10.1093/brain/awn013
64. Altenmüller E, Marco-Pallares J, Münte TF, Schneider S. Neural reorganization underlies improvement in stroke-induced motor dysfunction by music-supported therapy. Ann N Y Acad Sci. 2009;1169:395–405. [PMID:19673814] http://dx.doi.org/10.1111/j.1749-6632.2009.04580.x
65. Russo NM, Nicol TG, Zecker SG, Hayes EA, Kraus N. Auditory training improves neural timing in the human brainstem. Behav Brain Res. 2005;156(1):95–103. [PMID:15474654] http://dx.doi.org/10.1016/j.bbr.2004.05.012
66. Meyer M, Elmer S, Baumann S, Jancke L. Short-term plasticity in the auditory system: Differential neural responses to perception and imagery of speech and music. Restor Neurol Neurosci. 2007;25(3–4):411–31. [PMID:17943016]
67. Baumann S, Koeneke S, Schmidt CF, Meyer M, Lutz K, Jancke L. A network for audio-motor coordination in skilled pianists and non-musicians. Brain Res. 2007;1161: 65–78. [PMID:17603027] http://dx.doi.org/10.1016/j.brainres.2007.05.045
68. Koelsch S. A neuroscientific perspective on music therapy. Ann N Y Acad Sci. 2009;1169:374–84. [PMID:19673812] http://dx.doi.org/10.1111/j.1749-6632.2009.04592.x
69. Schneider S, Schönle PW, Altenmüller E, Münte TF. Using musical instruments to improve motor skill recovery following a stroke. J Neurol. 2007;254(10):1339–46. [PMID:17260171] http://dx.doi.org/10.1007/s00415-006-0523-2
70. Lohse KR, Lang CE, Boyd LA. Is more better? Using metadata to explore dose-response relationships in stroke rehabilitation. Stroke. 2014;45(7):2053–58. [PMID:24867924] http://dx.doi.org/10.1161/STROKEAHA.114.004695
71. Dobkin BH, Plummer-D'Amato P, Elashoff R, Lee J; SIRROWS Group. International randomized clinical trial, stroke inpatient rehabilitation with reinforcement of walking speed (SIRROWS), improves outcomes. Neurorehabil Neural Repair. 2010;24(3):235–42. [PMID:20164411] http://dx.doi.org/10.1177/1545968309357558
72. Choi Y, Gordon J, Park H, Schweighofer N. Feasibility of the adaptive and automatic presentation of tasks (ADAPT) system for rehabilitation of upper extremity function post-stroke. J Neuroeng Rehabil. 2011;8(1):42. [PMID:21813010] http://dx.doi.org/10.1186/1743-0003-8-42
73. Goodman RN, Rietschel JC, Roy A, Jung BC, Diaz J, Macko RF, Forrester LW. Increased reward in ankle robotics training enhances motor control and cortical efficiency in stroke. J Rehabil Res Dev. 2014;51(2):213–27. [PMID:24933720] http://dx.doi.org/10.1682/JRRD.2013.02.0050
74. Bragoni M, Broccoli M, Iosa M, Morone G, De Angelis D, Venturiero V, Coiro P, Pratesi L, Mezzetti G, Fusco A, Paolucci S. Influence of psychologic features on rehabilitation outcomes in patients with subacute stroke trained with robotic-aided walking therapy. Am J Phys Med Rehabil. 2013;92(10 Suppl 2):e16–25. [PMID:24052026] http://dx.doi.org/10.1097/PHM.0b013e3182a20a34
75. Haghgoo HA, Pazuki ES, Hosseini AS, Rassafiani M. Depression, activities of daily living and quality of life in patients with stroke. J Neurol Sci. 2013;328(1–2):87–91. [PMID:23522526] http://dx.doi.org/10.1016/j.jns.2013.02.027

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Feasibility of Wearable Sensing for In-Home Finger Rehabilitation Early After Stroke

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***Abstract* — Wearable grip sensing shows potential for hand rehabilitation, but few studies have studied feasibility early after stroke. Here, we studied a wearable grip sensor integrated with a musical computer game (MusicGlove). Among the stroke patients admitted to a hospital without limiting complications, 13% had adequate hand function for system use. Eleven subjects used MusicGlove at home over three weeks with a goal of nine hours of use. On average they achieved 4.1 +/- 3.2 (SD) hours of use and completed 8627 +/- 7500 grips, an amount comparable to users in the chronic phase of stroke measured in a previous study. The rank-order usage data were well fit by distributions that arise in machine failure theory. Users operated the game at high success levels, achieving note-hitting success >75% for 84% of the 1061 songs played. They changed game parameters infrequently (31% of songs), but in a way that logically modulated challenge, consistent with the Challenge Point Hypothesis from motor learning. Thus, a therapy based on wearable grip sensing was feasible for home rehabilitation, but only for a fraction of subacute stroke subjects. Subjects made usage decisions consistent with theoretical models of machine failure and motor learning.**

***Index Terms*— Wearable sensing, stroke, rehabilitation, hand movement, home therapy, music therapy**

I. Introduction

Upper limb sensorimotor function is severely impacted after stroke with about 80% of patients experiencing deficits early after symptom onset. Additionally, upper limb impairment persists in about 60% of patients 6 months post-stroke [1]. Intensive movement practice can help reduce hand impairment after stroke [2]–[7], but cost and accessibility limit an individual's ability to reach the high number of task repetitions thought necessary to improve recovery [8]–[10].

Home-based rehabilitation programs have been prescribed after stroke with the intent to increase the amount of rehabilitation exercise individuals can perform. The most common approach to home-based therapy is following a printed handout of exercises prescribed by a therapist. But, compliance with performing a list of exercises prescribed for in-home rehabilitation therapy is poor across a wide range of exercise types [11]–[15]. Thus, a critical outstanding question is how to motivate stroke patients to exercise in the home setting.

Several studies in the chronic phase (> 6 months post stroke) after stroke [15]–[19] have examined different strategies for in-home hand rehabilitation with mixed results. Modified constraint-induced movement therapy performed under the supervision of a nonprofessional coach in the home setting produced similar benefits compared to a program performed with a trained therapist in a clinical setting [16]. Greater self-reported use of the impaired limb in comparison to conventional therapy [17] was also observed. Another approach is tele-rehabilitation, which enables a therapist to guide training remotely. A systematic review of 10 trials with 933 total subjects found insufficient evidence to reach any substantial conclusions about the effectiveness of tele-rehabilitation after stroke, and most of these studies were applied in the chronic phase of stroke [20]. However, a recent study suggested that home-based telerehabilitation with a sensor-based system [21] that encouraged upper extremity movement practice following subacute stroke was not inferior to in-clinic training [19]. Other approaches to home-based hand rehabilitation include functional electrical stimulation [22], computer gaming with custom devices [23]–[25], and music-based therapy [26].

Fig. 1. MusicGlove device used in study. Users viewed a musical computer game that visually cued them using scrolling notes to make specific gripping movements in time with the notes. The device detects the movements using conductive finger pads. For the present study, the game was played on a 9 in. tablet computer.

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Despite the variety of options, it is still unclear which methods are the most viable for providing hand rehabilitation training at home, particularly early after a stroke (defined here as the first six months post stroke). Previous studies have shown that wearable movement sensors coupled with computer games can be motivating for rehabilitation [24], [27]–[29]. We explored this concept further by developing the MusicGlove device, an instrumented glove with sensors on each of the fingertips and the lateral aspect of the index finger (Fig. 1) [30], [31]. Home-based training by persons in the chronic phase of stroke led to significantly greater improvements in self-reported functional use of the impaired hand [32].

The present study sought to evaluate the feasibility of the MusicGlove as a home-based rehabilitation tool for individuals in the subacute period following stroke. Using such a wearable sensor soon after stroke at home raises several questions. First, as with many wearable sensors for hand rehabilitation, users need a moderate level of preserved hand function to effectively operate the MusicGlove. Users must be able to self-don it at home and complete the required gripping movements to play the associated computer game. Hence, the first feasibility goal of this study was to determine the fraction of individuals in the subacute phase of stroke who had adequate hand function to use such a wearable grip sensing approach.

Second, individuals in the subacute phase of stroke have just experienced a major life-changing event and are typically receiving standard-of-care rehabilitation therapy. They often have more medical appointments than people in the chronic phase after stroke, which might influence motivation to participate in additional therapies. A second feasibility goal was to determine if individuals in this population would use the MusicGlove as much as people in the chronic phase, as measured in an identical study protocol [32].

Third, a concern about self-administered care in the home setting is whether patients will appropriately challenge themselves. We therefore sought to characterize how users chose the game parameters that determined the challenge they experienced as they played.

Finally, we sought to establish a preliminary estimate of the effect of MusicGlove use on hand function in subacute stroke.

II. Methods

A. Study Design, Recruitment, and Inclusion Criteria

The University of California, Irvine (UCI) Institutional Review Board approved this randomized, controlled single-blind cross-over study, and all subjects provided informed consent prior to enrollment in the study. The study was designed to compare self-guided exercise with the MusicGlove to self-guided conventional hand therapy, both performed in the participant's home. The study was registered at ClinicalTrials.gov (NCT02410629). We included a control group because the original intent was to determine the therapeutic effect of MusicGlove. However, budgetary constraints and slow recruitment limited sample size, causing us to focus in this paper on feasibility rather than therapeutic results. Subjects were recruited by fliers distributed to local rehabilitation programs and by screening all new stroke subjects admitted at the UCI Medical Center. The inclusion criteria for the study are shown in Table I. Note that Table 1 contains more detail about the final cutoffs used for various impairments in comparison to the table presented on ClincialTrials.gov. Potential subjects who did not qualify for the study were re-assessed after a few weeks to determine if their hand recovery progressed to a level that would allow them to participate.

TABLE I
INCLUSION CRITERIA

18 to 80 years of age
History of stroke affecting the hand
Between 1-10 weeks post-stroke
Upper extremity weakness, defined as score of 15-62 (out of 66) on the Upper Extremity Fugl-Meyer Test
Able to perform at least 3 blocks on the Box and Blocks Test (BBT) but not greater than 80% of the score of the non-affected hand on the BBT
No other active major neurological disease other than stroke
Absence of severe pain in the stroke-affected upper extremity – score ≤ 3 on Visual Analog Pain scale
Absence of severe spasticity or contractures at the affected upper extremity (score <4 on the Modified Ashworth Scale)
Absence of severe aphasia
Absence of severe reduction in level of consciousness
Absence of severe sensory / proprioception deficit at the affected upper extremity (score of 0 in all categories of the Fugl-Meyer Sensory Examination)
Not currently pregnant
No active major psychiatric problems, or neurological/orthopedic problems affecting the stroke affected upper extremity
No difficulty in understanding or complying with instructions given by the experimenter
Able to perform the experimental task

B. Group Assignment and Intervention

In this cross-over design, a total of 11 subjects were randomized to receive either MusicGlove therapy first (MG 1st group) or conventional therapy (MG 2nd group) (Fig. 2). To ensure matched levels of impairment between groups, subjects were first stratified by their Box and Blocks Test (BBT) baseline score (3–30 or 30–60) and then assigned to a group by adaptive randomization [33]. The BBT is an established clinical measure of hand function that measures the number of blocks an individual can pick up and move over a divider in one minute; a normal score is about 60 blocks/min [34]. The MG 2nd group was trained to follow a booklet of conventional hand exercises [32] while the MG 1st group was trained to use a MusicGlove and tablet computer (Fig. 1) as their first intervention; training took about 30 minutes.

In the initial training session, the project therapist showed subjects how to play the game, including changing game difficulty parameters and how changing the parameters affected the game. The therapist also instructed subjects that they were free to change the difficulty of the games as they wished. When the subjects took the MusicGlove home, they started at whatever difficulty setting they chose. Subjects were asked to perform at least three hours of their intervention per week for three weeks.

Subjects were free to modulate the difficulty of their

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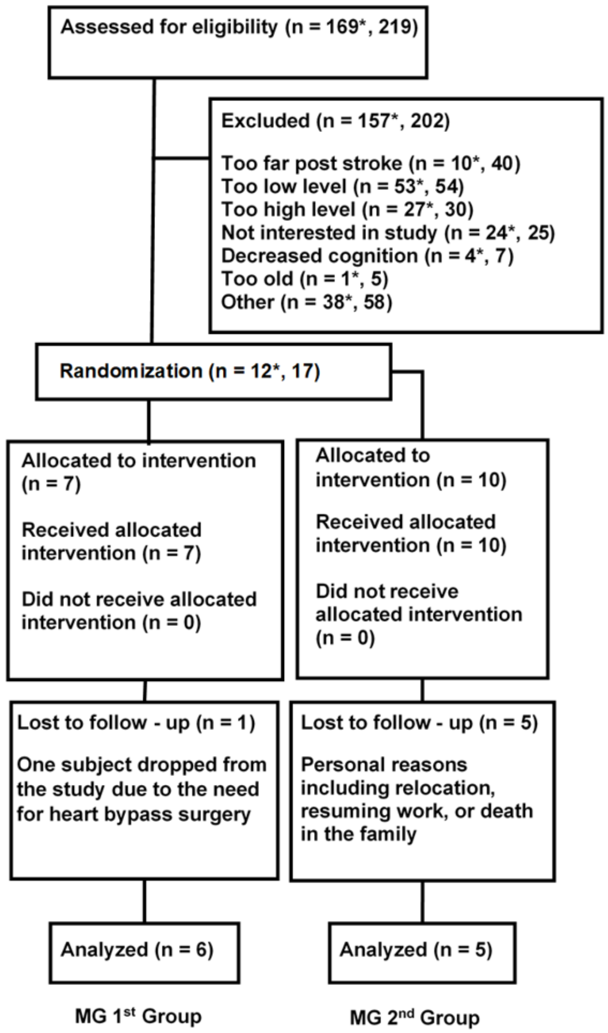

Fig. 2. Consolidated Standards of Reporting Trials Diagram. * denotes numbers from consecutively enrolled patients to a single hospital; the total number from all recruitment sources is shown as well.

MusicGlove training by changing the number of grip types (1-5: lateral pinch, index-thumb, middle-thumb, ring-thumb, pinky-thumb grips) needed to play, and/or by selecting songs at three different difficulty levels, where difficulty was determined by the number of target notes per minute of song. Subjects were also free to choose whether to play the game in “Song Mode” or “Session Mode”. In “Session Mode”, several songs at the same difficulty level are played in series and subjects can make changes to the game parameters after the series of songs has ended. Subjects could select series of 15, 30, 45, or 60 minutes in length. In “Song Mode” subjects could modify game parameters after each individually-selected song.

After the 3-week exercise period, the participants returned for a post therapy assessment, at which they returned the MusicGlove device or booklet of hand exercises. Then, after another 3-week period, they returned for the 3-wk follow-up assessment, followed by an assessment when they were 16-weeks post-stroke. At the 16-wk follow-up, individuals in the MG 2nd group were given the MusicGlove to use while individuals in the MG 1st group were given a booklet of hand therapy exercises. Each group matched the previous protocol, used the given intervention for three weeks, ceased activity for 3 weeks, and then returned for their follow-up at 6 months post stroke. During this study subjects received simultaneous rehabilitation therapy as part of their standard-of-care treatment. We did not control for the amount or content of this treatment as we deemed it both impractical and unethical.

C. *Outcome Measurements*

An experienced, blinded rehabilitation therapist performed a set of clinical assessments at baseline and at each additional time point during the study. We choose the follow-up periods (16-wk post-stroke, 6 months post-stroke) with respect to the onset of stroke as opposed to start of intervention in order to minimize the variance caused by spontaneous recovery, since the rate of spontaneous recovery varies depending on the time post stroke. The BBT score evaluated at the 3-wk post-intervention follow-up was preregistered on clinicaltrials.gov as the primary outcome measure. This paper focuses on this clinical measure of hand function only.

D. *Data Analysis*

We analyzed the data from periods of use of the MusicGlove device for usership metrics for each subject including: the success rate (# of notes completed / # of notes presented), amount of practice (as measured by the # of grips presented and the total usage time), and the types of in-game adjustments (i.e. changing song difficulty or grip types used). We assessed the distribution of the amount of grip practice by rank-ordering subjects, a common approach in non-parametric statistics. We used the R package *fitdistrplus* [35] to fit probability distributions to the data, and used Akaike Information Criterion (AIC) to evaluate goodness of fit.

We tested whether the probability of making a parameter change on the next song depended on the level of success achieved with the previous song using linear regression. For this analysis, we considered only songs that were not already at the lowest or highest difficulty levels. If the user increased the difficulty of one or both game parameters, we classified that as increasing game difficulty, and vice versa. Instances in which users increased one parameter and decreased the other were treated as no change in difficulty. The probability of changing the difficulty of the game was calculated for ranges of success using a sliding window of 10 jumping by 2 (i.e. success of previous song was between 0-10, then 2-12, etc.). Usership analyses were first applied to individual subjects, then averaged across all subjects.

III. Results

A. *Fraction of Subacute Stroke Patients Suitable for Device*

A total of 219 potential subjects were screened; 169 of these were stroke patients at a single university hospital and were available to enroll in the study (Fig. 2). Considering the consecutively screened stroke patients only, 92 met all other inclusion/exclusion criteria (Table I) before considering level of hand impairment. However, when considering hand impairment, 58% (53) of the consecutively screened potential subjects had too little hand function, 29% (27) had too high

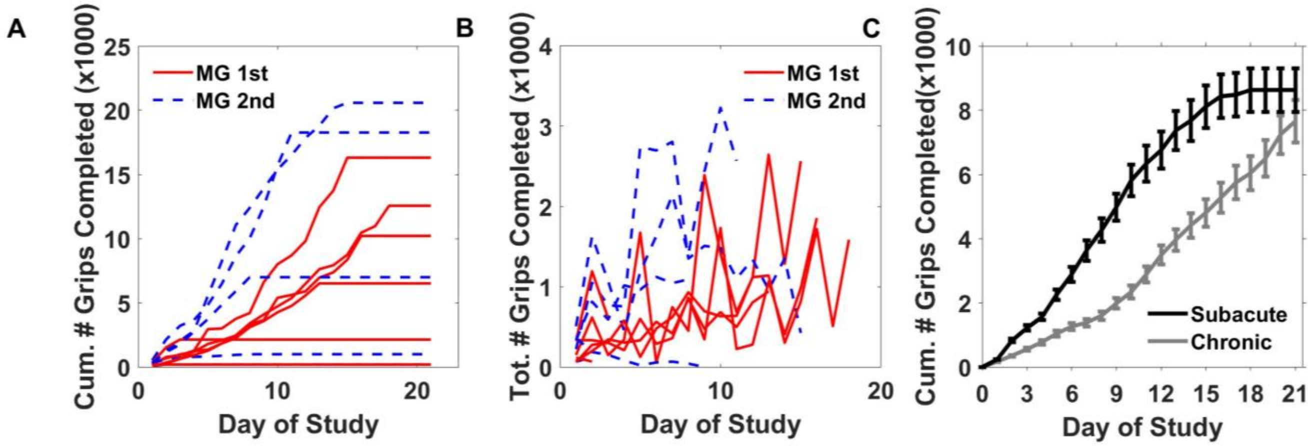

Fig. 3. Summary of usership of the MusicGlove device. **A**) The cumulative number of grips completed by each subject in the group that received the MusicGlove first (MG 1st), and the group that used the MusicGlove second, after three weeks of conventional home therapy (MG 2nd). **B)** The total number of grips completed each day by each subject for both groups. **C)** The average cumulative number of grips completed by the subjects from the current study compared to number completed by chronic stroke survivors from a previous study [30]. Bars show ± 1 SE.

hand function, and 13% (12) had an appropriate level of hand function and enrolled in the study. Five subjects referred from other hospitals also enrolled, for a total of 17.

Five subjects withdrew from the MG 1st group due to personal reasons including moving to a different country, resuming work, or a death in the family. One more subject

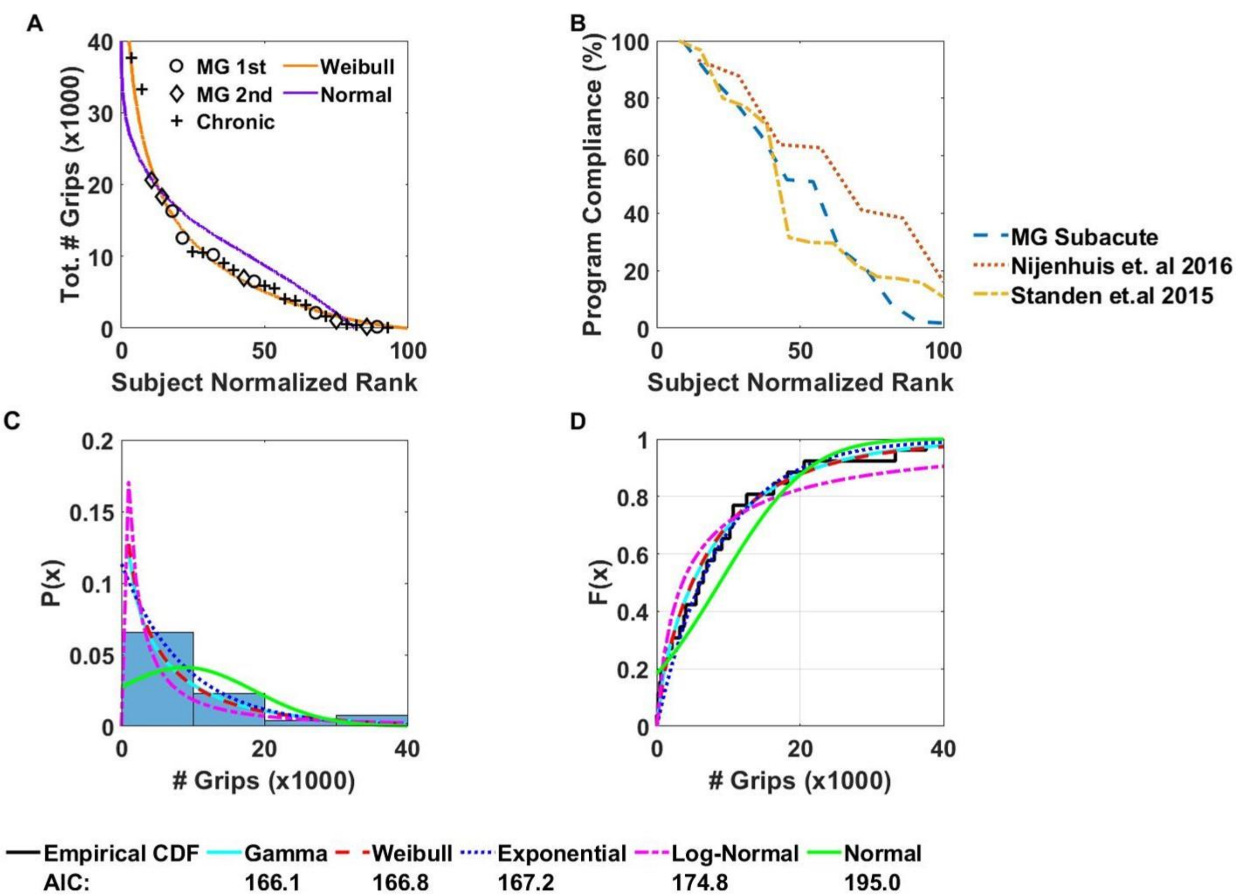

Fig. 4. Analysis of underlying distribution of grip data, and user program compliance. **A)** The total number of grips completed versus the subject normalized rank (subject number / total number of subjects *100). Data from present and previous study with chronic users are combined. A Weibull distribution (shape parameter $\lambda = 9400$, scale parameter $k = 0.96$) fit the data well, better than a normal distribution **B)** Program compliance (# of hours device used / recommended hours of use) versus the subject normalized rank. Each line represents a different study which utilized a different home rehabilitation technology for the upper extremity **C)** Histogram of the total number of grips completed by all subjects against the probability distribution function estimate. Each distribution's probability distribution is also plotted over the histogram. **D)** Empirical cumulative distribution function plotted against the theoretical cumulative distribution function of various distributions.

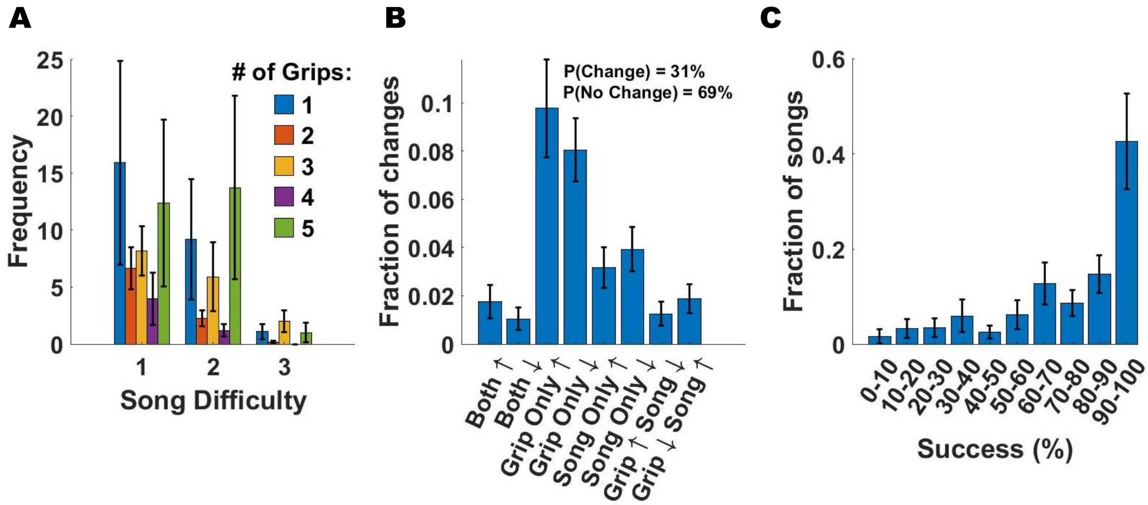

Fig. 5. Analysis of adjustments made to game parameters across 1061 songs, as well as analysis of success levels. Each color on the plots A, B, D, E represents a different subject while each dot represents one song. **A)** Scatter plot of the song difficulty (1: easiest, 3: hardest) versus the number of grip types used **B)** Fraction of different types of parameter changes. The percent of games were a parameter was not changed was 69%. **C)** Fraction of songs played at different success levels.

withdrew from the MG 2nd group due to the need to undergo heart surgery. Thus, there were a total of six subjects in the MG 1st group and five in the MG 2nd group who completed all research procedures.

B. Usage Patterns: Amount of Use

The MusicGlove computer logs revealed that the 11 subjects used the device on average 4.1 (+/- 3.2 SD) hours, which was 46% of the recommended 9 hours, and completed on average a total of 8627 (+/- 7500 SD) grips (Figure 3). This number of grips was comparable to the amount in the previous study of individuals in the chronic phase after stroke (mean 6953 +/- 6546 SD, t-test, p = 0.8) (Figure 3C) [30]. In this previous study, subjects followed an identical protocol. In the present study, the MG 1st group had an initial BBT score of 21 +/- 14 (compared to 33.0 +/- 10.6 in the prior study), while the MG 2nd group had an initial BBT score of 33 +/- 15 (compared to 32.6 +/- 10.6 in the prior study).

We compared this level of compliance in total use time to other studies of technologies for home rehabilitation of the upper extremity that report individual usage data (Fig 4B) [36], [37]. Both studies were conducted with chronic stroke survivors with the time-after-stroke being 32.8 +/- 12.0 and 91.3-weeks post stroke respectively. However, in [36] the intervention was a virtual reality glove while in [37] the intervention was a hand orthosis combined with an arm support system. In terms of the level of impairment subjects in [36] had an average Wolf Motor Function Test score of 3.8 +/- 3.9. While subjects in [37] had an average Fugl-Meyer Assessment score of 37.0. Note that in [37] only averages were given, and standard deviations were not reported. For comparison the average Fugl-Meyer Assessment score was 44.3 +/- 12.6 for the MG 1st group, and 42.4 +/- 8.7 for the MG 2nd group. In these studies, the average compliance was 58% and 46%. Additionally, when program compliance was plotted against the subject normalized rank for each study, they both followed a similar pattern that decreased continuously (i.e. subjects could not be classified easily as high and low users).

The difference between subacute and chronic study populations in cumulative amount of practice at each day during the study was not statistically significant (Fig. 3C). However, the subacute user group in the present study did, on average, significantly decrease the number of grips during week 3 compared to week 1 (paired t-test, p = .05), a pattern different from the chronic users, who significantly increased the number

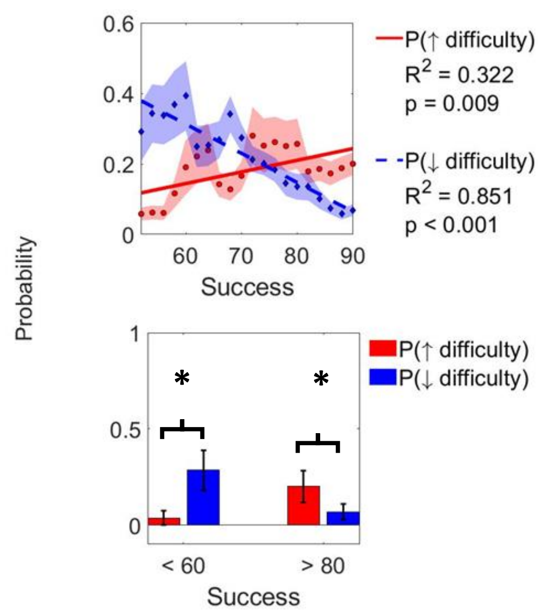

Fig. 6. **Top**. Probability of increasing (solid line) or decreasing (dashed line) game difficulty (via song difficulty or number of grips) as a function of success on previous song. Each point is a probability calculated based on all songs played within 10 points of success level of that point. We required at least 100 songs to plot a point. Since subjects rarely played at low success levels, no points below 65% success were included. **Bottom**. Comparison of probabilities of increasing or decreasing game difficulty at low and high success. * denotes p < 0.05.

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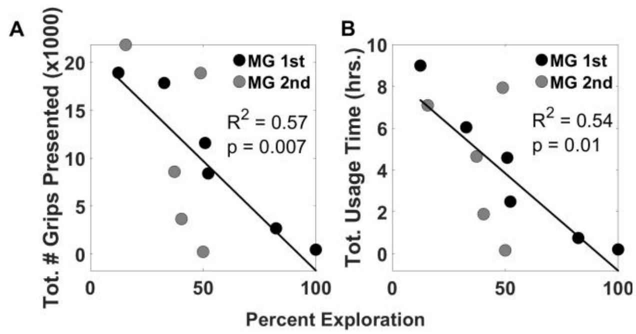

Fig. 7. Amount of practice of each subject from both groups represented as both the total number of grips presented and the total usage time versus the percent exploration. Percent exploration is defined as the total number of song parameter adjustments / total number of sessions played.

of grips during week 3 compared to week 1 (p = 0.008).

When we rank-ordered the users in terms of number of grips (Fig. 4A), we found that subjects again could not be grouped easily into clusters of high and low users. Rather, the rank-order distribution decreased smoothly, similar to the distribution from the previous chronic study. This led us to consider what type of probability distribution can generate this data. We combined data from the subacute and chronic studies for this analysis since they were not significantly different at any day (Fig. 4C). We found that the Gamma, Weibull, and Exponential fit the data well (Fig. 4D). These are related distributions that arise due to failure dynamics of machines, a connection we will return to in the Discussion.

C. Usage Patterns: Challenge Selection

Subjects predominately played the game at song difficulty levels 1 and 2 and rarely at the most difficult level 3 (Fig. 5A). They most frequently used 1 or 5 grip types (Fig. 5A). Subjects changed parameters after 31% of the songs, favoring changing the number of grips over song difficulty (Fig. 5B). They achieved note-hitting success of greater than 75% for 84% of the 1061 songs played (Fig. 5C).

The probability of subjects increasing difficulty of gameplay increased with success (linear regression, $R^2 = 0.32$, p = 0.009), and the probability of decreasing difficulty decreased with success ($R^2 = 0.85$, p < 0.001) (Fig. 6). The success level at which the probability of increasing and decreasing difficulty were equal was 74%. Even though the probability of increasing difficulty increased with higher success, note that there was still a finite chance that subjects decreased difficulty (~6% chance of decreasing difficulty at 90% success). The same pattern of randomness was true at low success levels (Fig. 6). When success was lower than 60% subjects were more likely to decrease the game difficulty (p = .05, two-tailed, paired t-test) while when success was higher than 80% subjects were more likely to increase game difficulty (p = .02).

The amount of practice (measured by either the number of grips presented or total usage time) was not correlated with the average level of success experienced or initial impairment level, measured with the BBT. However, the amount of practice (measured as total # of grips presented Fig. 7A or total usage time, Fig 7B) was inversely correlated with the amount of parameter exploration (defined as the total number of parameter adjustments/total number of songs played).

D. Preliminary Estimate of the Effect of MusicGlove on Hand Function

The average baseline BBT score prior to any intervention was 21 +/- 14 for the MG 1st group, and 33 +/- 15 for MG 2nd group (Fig. 8). The BBT score increased throughout the study. The MG 1st group had a greater average change in BBT score as compared to the MG 2nd group at all evaluations (e.g. 12 +/- 4 for MG 1st group vs 7 +/- 5 MG 2nd group at the end of the first phase of therapy). We did not perform a statistical analysis comparing groups because of the small sample size.

IV. Discussion

A. Feasibility of Using Wearable Sensing for Finger Rehabilitation at Home Early after Stroke

Like many wearable movement sensors for hand rehabilitation, the MusicGlove requires a moderate level of hand function to be used effectively as the user must engage the sensor for it to register that a movement has occurred. From our

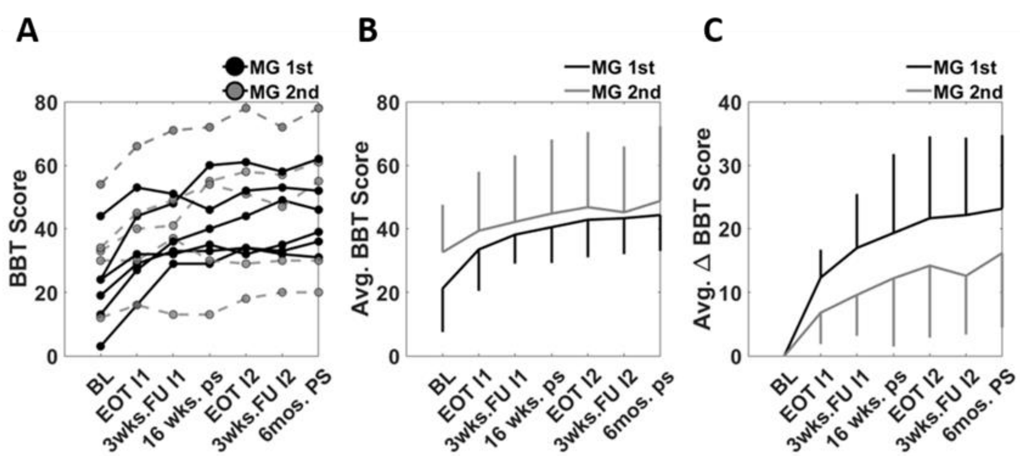

Fig. 8. **A)** Individual trajectories of BBT score throughout the study. **B)** The average BBT scores for the two groups. Vertical lines represent one SD. **C)** The average change in BBT score relative to the baseline evaluation.

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previous work we determined that individuals with a score of at least three on the BBT can reliably operate the device [31]. Here, we found that only ~13% of individuals 1-10 weeks post-stroke who met all other inclusion criteria also met this hand function criterion. Conversely, nearly 60% had too poor of hand function to participate. This observation indicates the importance of continuing to develop alternative hand training technologies, especially for people early after stroke when the brain is considered to be more receptive to rehabilitation.

One possible solution is to design sensors that allow more subtle movements to be detected. MusicGlove is limited by the use of contact sensing pads that require specific movements to be completed, and thus the features of "acceptable movements" cannot be varied. MusicGlove also only provides information about movement completion rather than real-time position data. A recent study that examined the percentage of subacute stroke subjects able to control mobile gaming technologies found that about 60% could use the paretic hand to control a cursor with a tablet or smartphone with swiping motions, and 93% could control a cursor with isometric grip force control [38]. Such interfaces, coupled with games, could help make home-based hand training more accessible to more people with stroke.

Another possible solution is to add actuation to the device to physically assist the user in making gripping movements. However, adding actuation doesn't solve the problem that the user must still generate hand-related control signals to activate the assistance. Robotic assistance applied to a passive user has little therapeutic benefit [39]. Detecting movement-related signals at the level of the brain [40][41] or muscle [42], rather than relying on the resulting movement itself, is a possible solution, but increases complexity for home use because of the requirement to apply electrodes.

B. *Usership of MusicGlove: Amount of Use*

For subacute subjects with adequate hand function, using the MusicGlove was feasible. On average, the subjects in the present study utilized the system to achieve a number of grips slightly greater than the number that was completed by chronic stroke survivors in the previous study. Thus, the life circumstances associated with the subacute phase of stroke did not limit engagement with this technology. However, on average, the subacute users significantly decreased their usage over time, a pattern different from chronic users. Perhaps their ongoing spontaneous hand recovery contributed to more rapid abandonment. Alternately, they may have had relatively more untried therapy options available compared to chronic users, and abandoned MusicGlove in favor of exploring those options. One other possible explanation could that these are receiving standard-of care rehabilitation therapy and thus have an increased amount of medical appointments. This increased busy-ness could interfere with research procedures [43].

Despite achieving a relatively large number of grips on average (> 8000), user compliance was moderate (46%) in completing the requested hours of use. Few studies exist that were conducted in the home setting with subjects from the sub-acute stroke population that report individual usage data, making direct comparisons difficult. Although the other home-based studies compared in this manuscript (Fig. 4B) were conducted with subjects from the chronic stroke population, they provide a start for understanding compliance with upper extremity rehabilitation devices in the home setting. In the current study moderate user compliance may have arisen in part due to poorer motivation to use the device amongst users with higher hand function, although amount of practice was not correlated with initial or final BBT score. Continuing to understand the factors influencing compliance is an important direction for future work.

Some insight might be gained by considering the distribution of amount of practice. We found that the Gamma and Weibull distributions fit the data well in comparison to a Normal distribution. These related distributions are commonly used to model machine failure. For example, a Gamma distribution arises as a time-to-first-fail distribution for a redundant system. If there are n-1 backup units and all backup units have exponential lifetimes, then the total lifetime has a Gamma distribution [44]. The Weibull distribution characterizes the time to failure for many machines [45]. This is because machines are typically made of many parts, each of which can cause the machine to fail. When each part lasts a minimum time, but then fails probabilistically, Extreme Value Theory can be used to show that the Weibull distribution arises for weak conditions on the part failure probability distributions [45]. It may be possible to draw an analogy to understand usership patterns of home rehabilitation technology. For example, there are dozens of probabilistic factors (e.g. psychological, technological, sociological, cultural, neurologic) that can cause a person to stop practicing with a home-based rehabilitation technology, and each likely has a minimum time to "activate". Thus, one would expect usage to follow a Weibull distribution. The fact that a Weibull distribution fit the data well then suggests usership may rely on a large number of subject specific factors. Exploring the use of machine failure theory and reliability analysis to gain insight into home usership is an interesting future research direction.

C. *Usership of MusicGlove: Challenge Selection*

The Challenge Point Hypothesis (CPH) from the motor learning literature posits that there is an optimal task difficulty for promoting skill development [46]. The CPH has been proposed to apply to rehabilitation as well [47]. In the context of movement recovery, rehabilitation therapists normally select an appropriate challenge level for each patient for each therapy task, consist with the CPH. A concern about self-administered care in the home setting is whether patients will challenge themselves enough during therapy. In the present study, we allowed the user to modify at will two parameters that affected the challenge of training. A key question was whether they would use this ability in a way consistent with the CPH.

We observed that the subjects tended to leave the parameters at a level that allowed them to play the game at high success levels (>75% success for 84% of songs), infrequently making changes to the parameters (on only 31% of songs), though higher difficulty settings were available. When they adjusted parameters, they did so in a way consistent with the CPH - tending to increase difficulty if their success at the last song was

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high, or decrease difficulty if success was low. The magnitude of these changes was low (14% increase across a change in success of 40%). These findings illustrates that 1) users tended to not make changes to difficulty; 2) when users did make a change they tended to do the logical thing (increasing difficulty when success is high, and decreasing difficulty when success is low); 3) user behavior was stochastic or explorative, as there was still a finite probability users did the "illogical" thing (increase difficulty when success was low).

Within the stroke rehabilitation technology literature there exist many examples of adaptive algorithms for adjusting task difficulty based on movement performance [48]. These algorithms often adapt task parameters to modulate the level of challenge experienced by the user after each sensed movement attempt. These types of algorithms are thought to be advantageous as they can be tuned to provide assistance matching an individual's changing needs. However, we observed in the current study that people infrequently made changes to the game parameters. Further, subjects who exhibited less exploration (defined as total number of game adjustments / total number of songs played) used the system more. This suggests that if we are to make algorithms that more closely align with desirable human usership behavior, a less aggressive (i.e. not adapting as often) and more stochastic approach (i.e. sometimes adapting in the "wrong" direction) may be warranted.

We also recently found in a study of robotic finger training that training with a higher success level (80% - generated by robotic assistance) resulted in higher motivation and better long-term retention, particularly for more-impaired users [49]. The fact that the subjects in the present study preferred similarly high success levels, coupled with their CPH-consistent parameter adjustment behavior, suggests that persons with a stroke indeed have intuition about how best to practice.

An interesting possibility is to more rigorously characterize each home user as a stochastic decision process and analyze whether subject-specific decision rules predict greater usage or better therapeutic results. Such analyses will require larger data sets, which hopefully will become available with the growth of home-based commercial rehabilitation technologies.

D. Limitations and Directions for Future Research

Budgetary constraints coupled with the small percentage of people who could qualify for the study hindered our ability to recruit the planned number of subjects for the study (N = 20 for each group). The small sample size, plus the fact the MG 2nd group had a higher baseline BBT score, made it unfeasible to directly compare the therapeutic effect of MG 1st to MG 2nd in the first training phase. However, the data provide an initial estimate of effect size, which can be useful for planning future studies. The data were also suggestive that earlier access to the MG produced a larger change in BBT score. These findings support conducting larger efficacy studies to test whether MusicGlove or other movement sensors for hand training can facilitate quicker or larger recovery of fine motor function.

We asked subjects to log their conventional hand training, but they did not consistently do so. Thus, we could not make comparisons in compliance or analyze possible dose effects of the conventional training approach. The amount of difficulty adjustment we observed may have been influenced by the instructions and by how subjects interpreted them. The influence of pre-training on the way users use home rehabilitation technology is an interesting topic for future research. We pooled subjects from the MG 1st and MG 2nd groups for analysis. There may have been order effects, such as that subjects in the MG 2nd had a lower level of hand impairment when they started using the MusicGlove because of ongoing recovery. However, we found significant effects for the combined group even with this possible source of increased variance.

V. Conclusion

Only a small fraction of consecutively enrolled stroke patients could qualify for this study, having the appropriate level of hand function for using a wearable movement sensor-based rehabilitation approach, and meeting the other inclusion criteria. This suggests that further research needs to be done to develop devices that can help a larger proportion of people who have a severe hand impairment early after stroke. Among the population with the required amount of hand function, the sensor and musical game presented in this study were feasible for autonomous home use and caused no adverse effects. We found a possible connection between machine failure theory and usership via the form of the distribution of amount of use. We also observed that subjects played mostly at high success levels, infrequently making parameter changes when playing the game. When they did make changes, they did so in a way consistent with the Challenge Point Hypothesis, but with an element of randomness suggestive of exploration. These analyses point to the need to analyze "in-the-wild" user decisions in larger populations to understand how usage patterns might be associated with longer and/or more effective use of rehabilitation devices.

References

[1] A. Schwarz, C. M. Kanzler, O. Lambercy, A. R. Luft, and J. M. Veerbeek, "Systematic review on kinematic assessments of upper limb movements after stroke," *Stroke*, vol. 50, no. 3, pp. 718–727, 2019.

[2] S. C. Cramer, "The EXCITE trial: A major step forward for restorative therapies in stroke," *Stroke*, vol. 38, no. 7, pp. 2204–2205, 2007.

[3] L. Sawaki, "Use-dependent plasticity of the human motor cortex in health and disease," *IEEE Eng Med Biol Mag*, vol. 24, no. 1, pp. 36–9., 2005.

[4] L. Ada, S. Dorsch, and C. G. Canning, "Strengthening interventions increase strength and improve activity after stroke: a systematic review.," *Aust. J. Physiother.*, vol. 52, no. 4, pp. 241–8, 2006.

[5] van der L. JH, S. IA, H. Beckerman, L. GJ, W. RC, and B. LM, "Exercise therapy for arm function in stroke patients: a systematic review of randomized controlled trials.," *Clin Rehabil*, vol. 15(1), no. 01, pp. 20–31, 2001.

[6] M. G. Kloosterman, G. J. Snoek, and M. J. Jannink, "Systematic review of the effects of exercise therapy on the upper extremity of patients with spinal-cord injury," *Spinal cord Off. J. Int. Med. Soc. Paraplegia*, 2008.

[7] R. J. Nudo, "Postinfarct cortical plasticity and behavioral recovery," *Stroke*, vol. 38, no. 2 PART 2, pp. 840–845, 2007.

[8] C. E. Lang *et al.*, "Observation of Amounts of Movement Practice

Provided During Stroke Rehabilitation," *Arch. Phys. Med. Rehabil.*, vol. 90, no. 10, pp. 1692–1698, 2009.

[9] N. N. Byl, E. a Pitsch, and G. M. Abrams, "Functional outcomes can vary by dose: learning-based sensorimotor training for patients stable poststroke.," *Neurorehabil. Neural Repair*, vol. 22, no. 5, pp. 494–504, 2008.

[10] M. S. Jeffers *et al.*, "Does Stroke Rehabilitation Really Matter? Part B: An Algorithm for Prescribing an Effective Intensity of Rehabilitation," *Neurorehabil. Neural Repair*, vol. 32, no. 1, pp. 73–83, 2018.

[11] K. L. Cox, V. Burke, T. J. Gorely, L. J. Beilin, and I. B. Puddey, "Controlled comparison of retention and adherence in home- vs center-initiated exercise interventions in women ages 40-65 years: The S.W.E.A.T. Study (Sedentary Women Exercise Adherence Trial).," *Prev Med*, vol. 36, pp. 17–29, 2003.

[12] W. J. Rejeski, L. R. Brawley, W. Ettinger, T. Morgan, and C. Thompson, "Compliance to exercise therapy in older participants with knee osteoarthritis: implications for treating disability.," *Med Sci Sport. Exerc*, vol. 29, pp. 977–985, 1997.

[13] E. M. Sluijs, G. J. Kok, and J. Van Der Zee, "Correlates of Exerice Compliance in Physical Therapy," *Phys. Ther.*, vol. 73, no. 1, pp. 771–782, 1993.

[14] A. Turton and C. Fraser, "The use of home therapy programmes for improving recovery of the upper limb following stroke," *Br. J. Occup. Ther. 1990 Nov;53(11)457-462*, vol. 53, no. November, pp. 457–462, 1990.

[15] M. T. Jurkiewicz, S. Marzolini, and P. Oh, "Adherence to a home-based exercise program for individuals after stroke.," *Top. Stroke Rehabil.*, vol. 18, no. 3, pp. 277–284, 2011.

[16] A. Barzel *et al.*, "Comparison of two types of Constraint-Induced Movement Therapy in chronic stroke patients: A pilot study," *Restor. Neurol. Neurosci.*, vol. 27, no. 6, pp. 673–680, 2009.

[17] A. Barzel *et al.*, "Enhancing activities of daily living of chronic stroke patients in primary health care by modified constraint-induced movement therapy (HOMECIMT): study protocol for a cluster randomized controlled trial.," *Trials*, vol. 14, p. 334, 2013.

[18] L. Dodakian *et al.*, "A Home-Based Telerehabilitation Program for Patients With Stroke," *Neurorehabil. Neural Repair*, vol. 31, no. 10–11, pp. 923–933, 2017.

[19] S. C. Cramer *et al.*, "Efficacy of Home-Based Telerehabilitation vs In-Clinic Therapy for Adults after Stroke: A Randomized Clinical Trial," *JAMA Neurol.*, 2019.

[20] K. E. Laver, D. Schoene, M. Crotty, S. George, N. A. Lannin, and C. Sherrington, "Telerehabilitation services for stroke," *Cochrane Database Syst. Rev.*, vol. 2013, no. 12, 2013.

[21] L. Dodakian *et al.*, "A home-based telerehabilitation program for patients with stroke," *Neurorehabil. Neural Repair*, vol. 31, no. 10–11, pp. 923–933, 2017.

[22] Y. Hara, S. Ogawa, K. Tsujiuchi, and Y. Muraoka, "A home-based rehabilitation program for the hemiplegic upper extremity by power-assisted functional electrical stimulation.," *Disabil. Rehabil.*, vol. 30, no. 4, pp. 296–304, 2008.

[23] E. V. Donoso Brown, S. W. McCoy, A. S. Fechko, R. Price, T. Gilbertson, and C. T. Moritz, "Preliminary investigation of an electromyography-controlled video game as a home program for persons in the chronic phase of stroke recovery," *Arch. Phys. Med. Rehabil.*, vol. 95, no. 8, pp. 1461–1469, 2014.

[24] M. King, J. Hijmans, M. Sampson, J. Satherley, and L. Hale, "Home-based stroke rehabilitation using computer gaming," *New Zeal. J. Physiother.*, vol. 40, no. 3, pp. 128–134, 2012.

[25] A. Slijper, K. E. Svensson, P. Backlund, H. Engström, and K. S. Sunnerhagen, "Computer game-based upper extremity training in the home environment in stroke persons: a single subject design.," *J. Neuroeng. Rehabil.*, vol. 11, p. 35, 2014.

[26] M. Villeneuve and A. Lamontagne, "Playing piano can improve upper extremity function after stroke: Case studies," *Stroke Res. Treat.*, 2013.

[27] J. M. Hijmans, L. a. Hale, J. a. Satherley, N. J. McMillan, and M. J. King, "Bilateral upper-limb rehabilitation after stroke using a movement-based game controller," *J. Rehabil. Res. Dev.*, vol. 48, no. 8, p. 1005, 2011.

[28] J. Yoo, "The Role of Therapeutic Instrumental Music Performance in Hemiparetic Arm Rehabilitation," *Music Ther. Perspect.*, vol. 27, no. 1, pp. 16–24, 2009.

[29] P. Rinne *et al.*, "Democratizing neurorehabilitation:how accessible are low-cost mobile-gaming technologies for self-rehabilitation of arm disability in stroke?," *PLoS One*, vol. 11, no. 10, 2016.

[30] N. Friedman, V. Chan, D. Zondervan, M. Bachman, and D. J. Reinkensmeyer, "MusicGlove: Motivating and quantifying hand movement rehabilitation by using functional grips to play music," in *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, 2011.

[31] N. Friedman *et al.*, "Retraining and assessing hand movement after stroke using the MusicGlove: comparison with conventional hand therapy and isometric grip training," *J. Neuroeng. Rehabil.*, vol. 11, no. 1, p. 76, 2014.

[32] D. K. Zondervan *et al.*, "Home-based hand rehabilitation after chronic stroke: Randomized, controlled single-blind trial comparing the MusicGlove with a conventional exercise program," *J. Rehabil. Res. Dev.*, vol. 53, no. 4, pp. 457–472, 2016.

[33] C. Meinert and S. Tonascia, *Clinical trials: Design, conduct, and analysis*. New York: Oxford University Press, 1986.

[34] V. Mathiowetz, G. Volland, N. Kashman, and K. Weber, "Adult norms for the Box and Block Test of manual dexterity.," *Am. J. Occup. Ther. Off. Publ. Am. Occup. Ther. Assoc.*, vol. 39, no. 6, pp. 386–391, 1985.

[35] M. L. Delignette-Muller and C. Dutang, "fitdistrplus: An R package for fitting distributions," *J. Stat. Softw.*, 2015.

[36] P. J. Standen *et al.*, "Innovative Technologies Special Series," vol. 95, no. 3, 2015.

[37] S. Nijenhuis, G. Prange, F. Amirabdollahian, F. Infarinato, J. Buurke, and J. Reitman, "Feasibility of a second iteration wrist and hand supported training system for self-administered training at home in chronic stroke," *eighth Int. Conf. eHealth, telemedicine, Soc. Med.*, 2016.

[38] P. Rinne *et al.*, "Democratizing neurorehabilitation:how accessible are low-cost mobile-gaming technologies for self-rehabilitation of arm disability in stroke?," *PLoS One*, vol. 11, no. 10, pp. 1–12, 2016.

[39] X. L. Hu, K.-Y. Tong, R. Song, X. J. Zheng, and W. W. F. Leung, "A comparison between electromyography-driven robot and passive motion device on wrist rehabilitation for chronic stroke.," *Neurorehabil. Neural Repair*, vol. 23, no. 8, pp. 837–46, Oct. 2009.

[40] C. M. McCrimmon, C. E. King, P. T. Wang, S. C. Cramer, Z. Nenadic, and A. H. Do, "Brain-controlled functional electrical stimulation therapy for gait rehabilitation after stroke: a safety study.," *J. Neuroeng. Rehabil.*, vol. 12, p. 57, Jul. 2015.

[41] S. L. Norman *et al.*, "Controlling pre-movement sensorimotor rhythm can improve finger extension after stroke," *J. Neural Eng.*, vol. 15, no. 5, Aug. 2018.

[42] R. A. Bos *et al.*, "A structured overview of trends and technologies used in dynamic hand orthoses," *Journal of NeuroEngineering and Rehabilitation*, vol. 13, no. 1. 2016.

[43] S. C. Cramer *et al.*, "Stroke Recovery and Rehabilitation Research: Issues, Opportunities, and the National Institutes of Health StrokeNet," *Stroke*, vol. 48, no. 3, pp. 813–819, 2017.

[44] J. Inglis, W. Q. Meeker, and L. A. Escobar, "Statistical Methods for Reliability Data," *J. Am. Stat. Assoc.*, 2000.

[45] E. Castillo, *Extreme value theory in engineering*. Academic Press, 1988.

[46] M. A. Guadagnoll and T. D. Lee, "Challenge Point: A Framework for Conceptualizing the Effects of Various Practice Conditions in Motor Learning," *Journal of Motor Behavior*, vol. 36, no. 2. pp. 212–224, Jun-2004.

[47] D. A. Brown, T. D. Lee, D. J. Reinkensmeyer, and J. E. Duarte, *Designing robots that challenge to optimize motor learning*. 2016.

[48] L. Marchal-Crespo and D. J. Reinkensmeyer, "Review of control strategies for robotic movement training after neurologic injury," *J. Neuroeng. Rehabil.*, vol. 6, no. 1, 2009.

[49] J. B. Rowe, V. Chan, M. L. Ingemanson, S. C. Cramer, E. T. Wolbrecht, and D. J. Reinkensmeyer, "Robotic Assistance for Training Finger Movement Using a Hebbian Model: A Randomized Controlled Trial," *Neurorehabil. Neural Repair*, vol. 31, no. 8, 2017.