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

Vinesh Janarthanan [a], Md Assad-Uz-Zaman MSc Eng [a], Mohammad Habibur Rahman PhD [a,*], Erin McGonigle MD [b], Inga Wang PhD [c]

[a] BioRobotics Lab, Mechanical/Biomedical Engineering, University of Wisconsin Milwaukee (UWM), WI, USA
[b] Physical Medicine and Rehabilitation, Medical College of Wisconsin, WI, USA
[c] Occupational Science and Technology, College of Health Science, UWM, WI, USA

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

* Corresponding author. University of Wisconsin Milwaukee (UWM), WI 53211, USA.
E-mail address: rahmanmh@uwm.edu (M.H. Rahman).

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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)

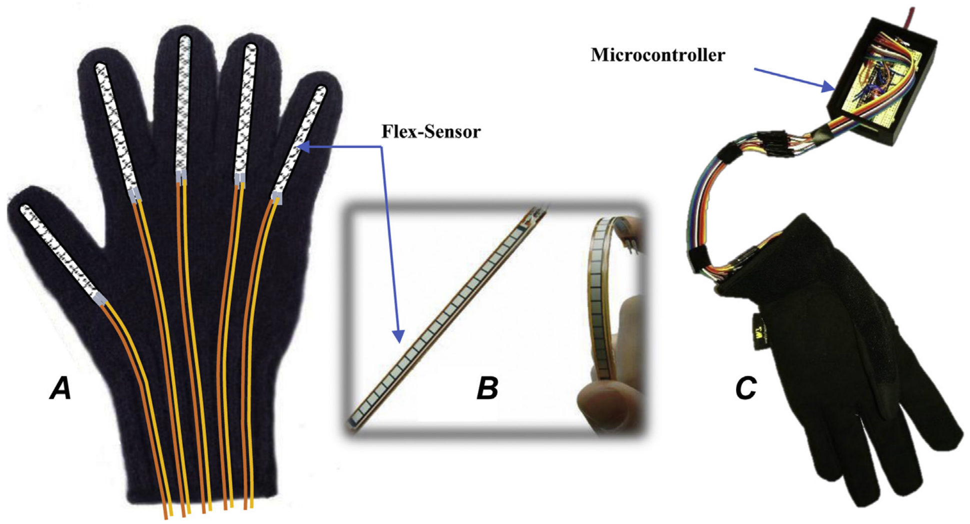

Fig. 1. Sensored glove system; **(A)** schematic of flex sensors instrumentation on the glove; **(B)** Flex sensor; and **(C)** developed sensored rehab glove with the circuitry open for display.

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,

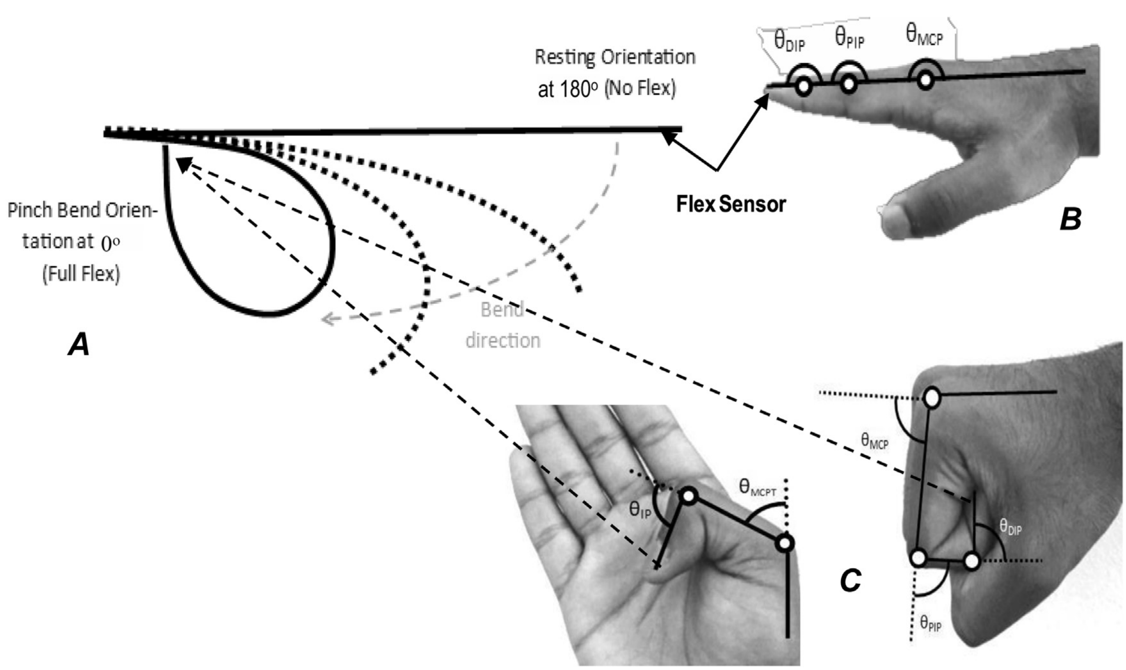

Fig. 2. MCP, PIP, and DIP flexion/extension estimation from flex sensor. **(A)** Schematic diagram of the resistive flex sensor shows the resting orientation (180°) and the fully flexed position (0°); **(B)** resting state of MCP, DIP, IP, MCPT, and PIP joints (where, $\theta_{MCP} = 180°$, $\theta_{DIP}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

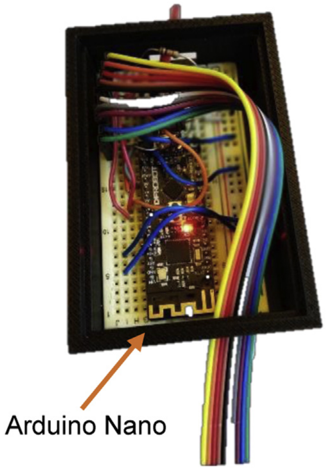

Fig. 3. Arduino, breadboard, and all electrical instrumentation housed in a 3D printed case.

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

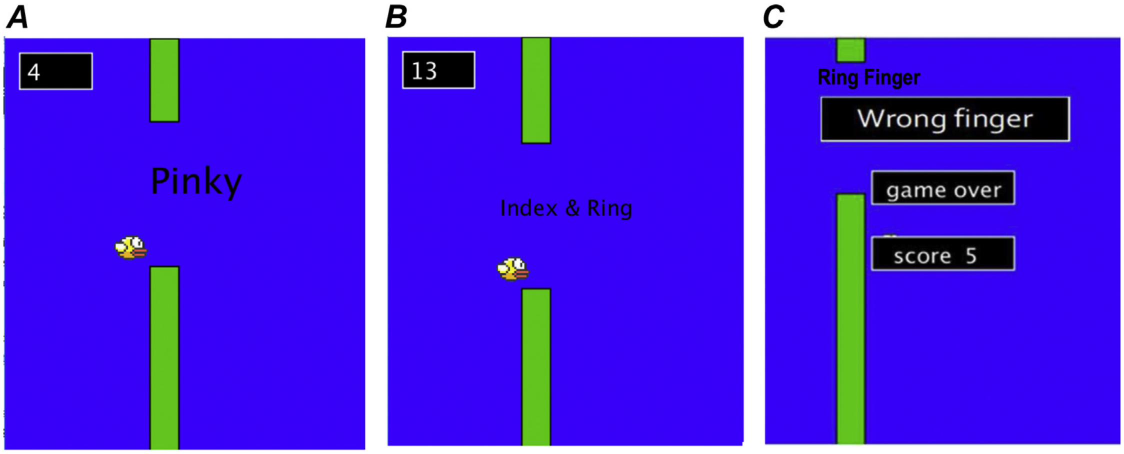

Fig. 4. Three screenshots of the game are presented to show what the game looks like and how it functions. **(A)** This screenshot depicts a player with a score of 4 points, and the game asks the player to flex her pinky finger; **(B)** this screenshot presents a multifinger motion exercise that the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

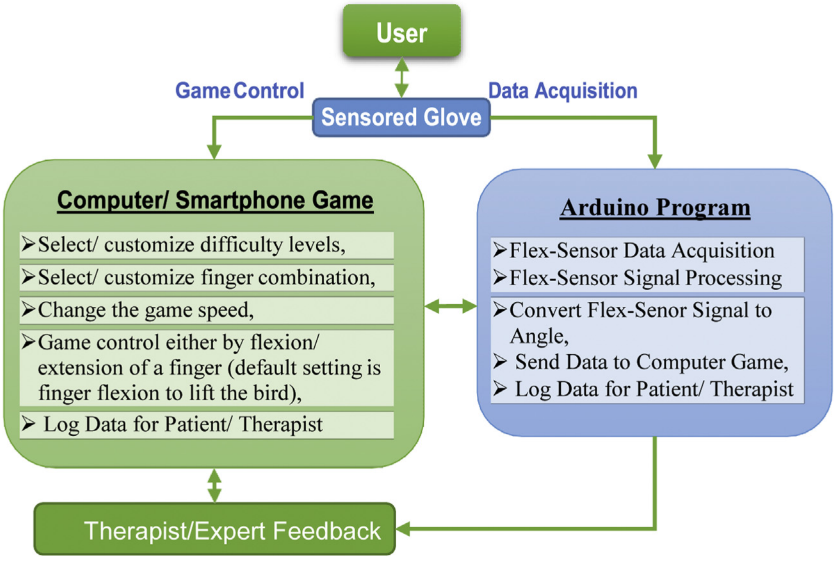

Fig. 5. Block diagram showing an overview of how the therapeutic process with the developed sensored glove works.

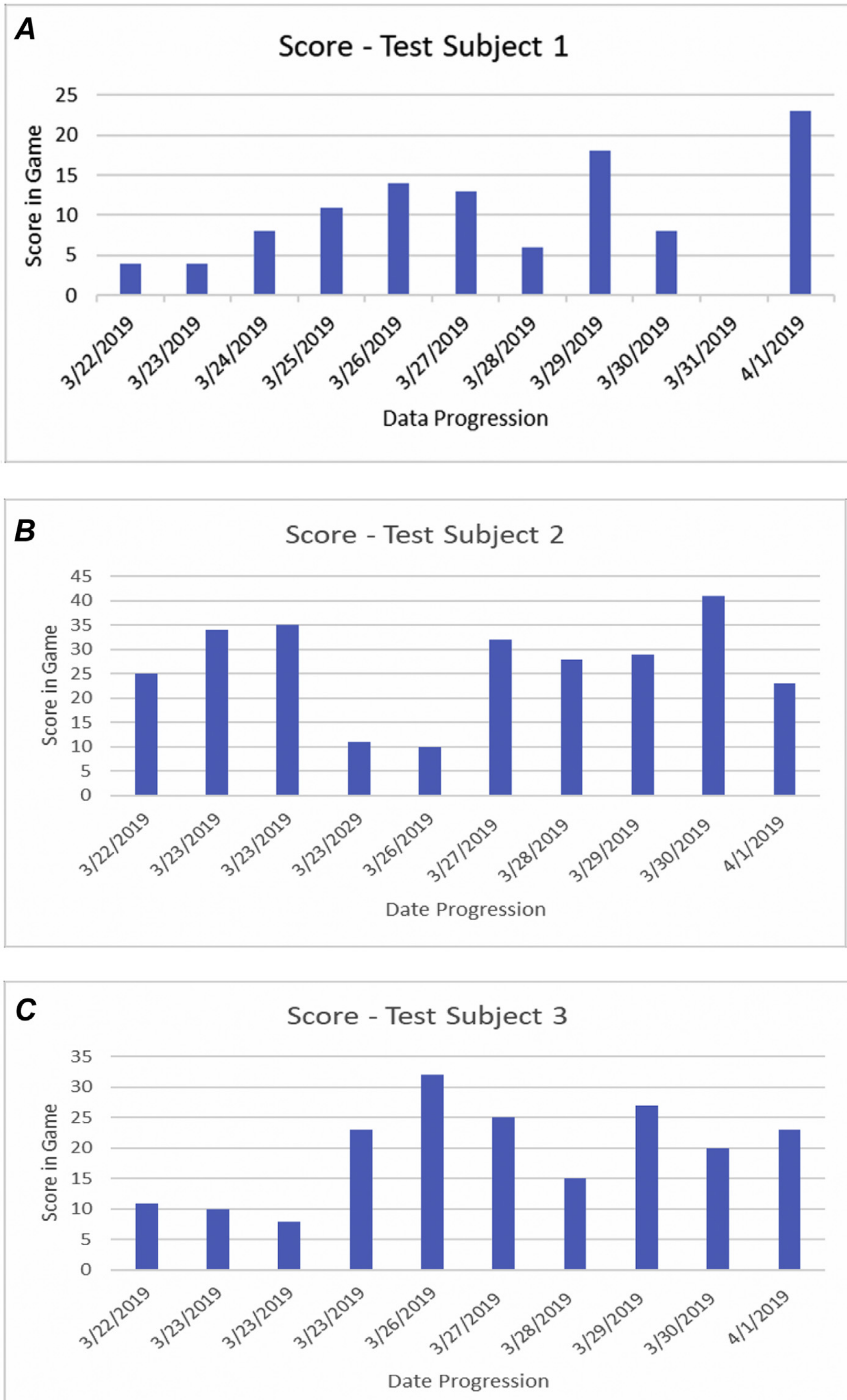

Fig. 6. The game score received throughout the 10 days, **(A)** subject 1's logbook; **(B)** subject 2's logbook, and **(C)** subject 3's logbook.

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.

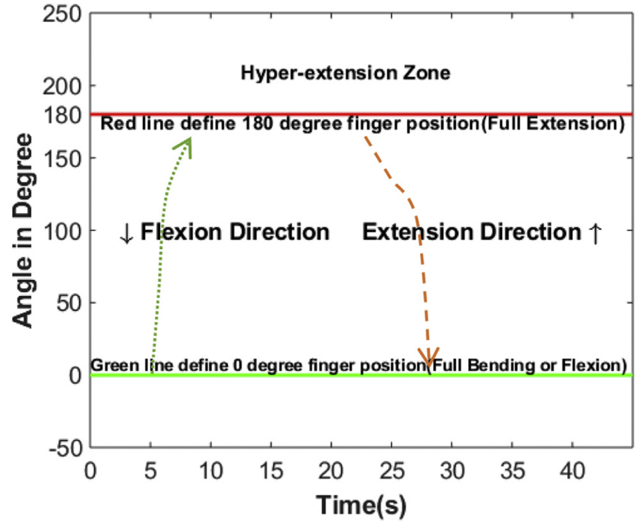

Fig. 7. Nomenclature for data representation.

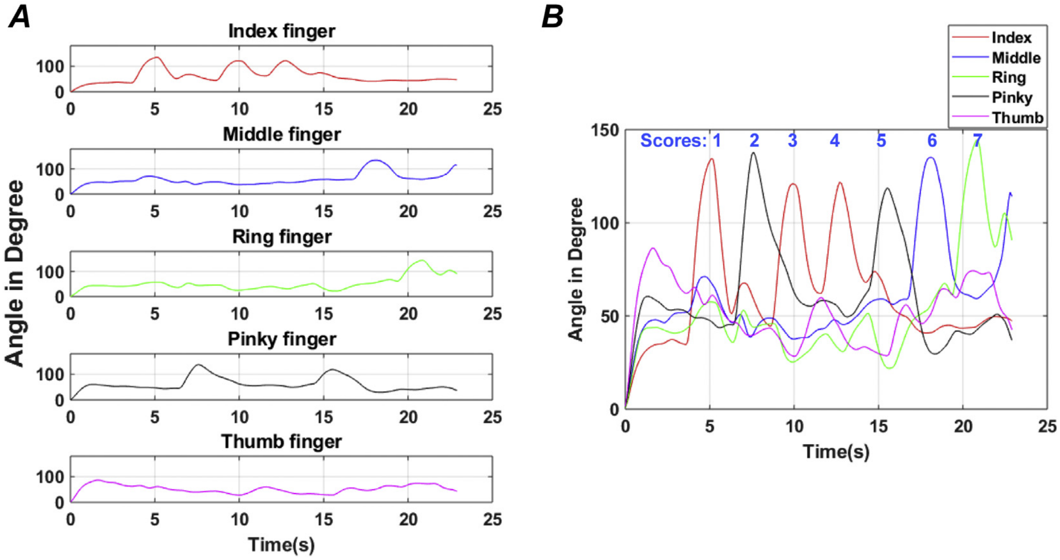

Fig. 8. The experimental result with subject 1 scored 7 on March 24th for finger extension movement; **(A)** individual finger movement plots; **(B)** results shown in panel **(A)** are plotted in one graph. No simultaneous motion of multifingers can be seen on panel **(B)** as the subject's score was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

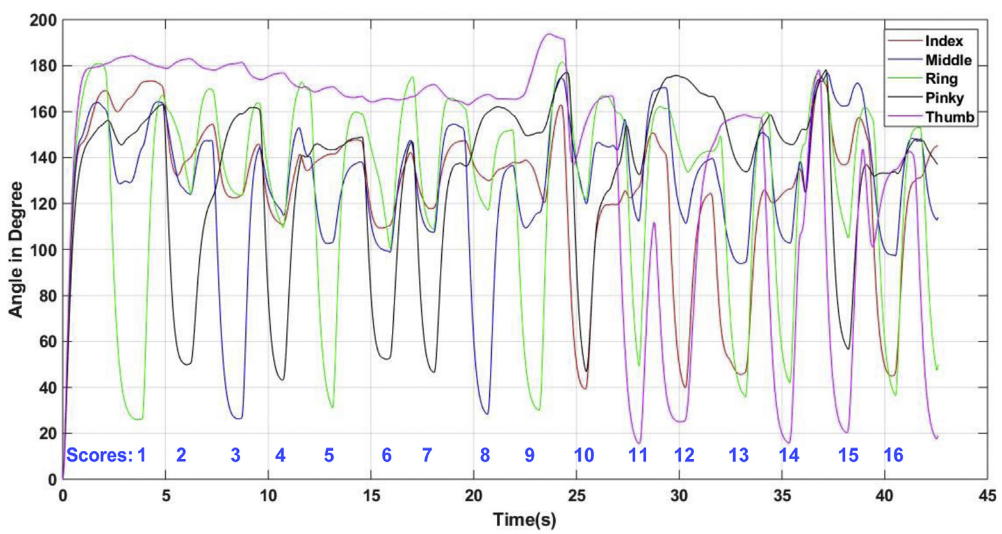

Fig. 9. The experimental result with subject 2 scored 16 for the finger flexion movement. A double finger combination appeared on the figure after the subject's score reaches 10.

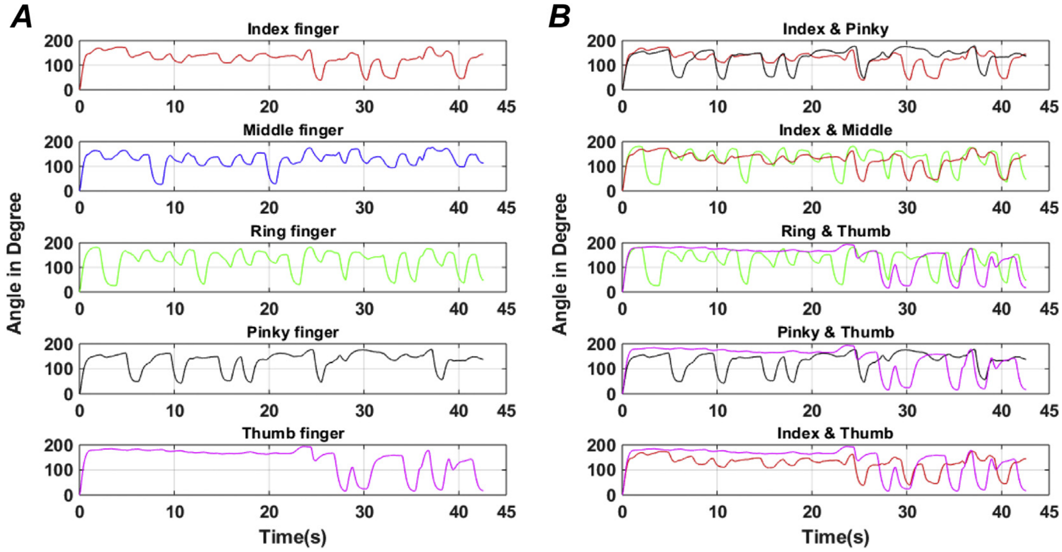

Fig. 10. **(A)** Individual finger joint angles extracted from Fig. 9; **(B)** simultaneous flexion motion of two fingers extracted from Fig. 9.

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

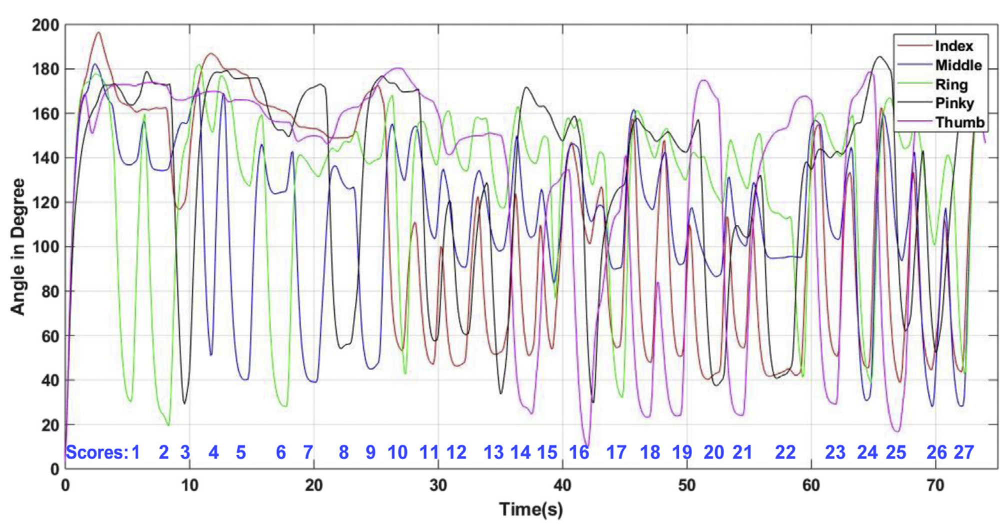

Fig. 11. The experimental result with subject 3 scored 27 for finger flexion movement. Double and triple finger combination appeared on the figure after the subject's score increases.

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.

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