An Automated Game-Based Variable-Stiffness Exoskeleton for Hand Rehabilitation

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***Abstract*— In this paper, we propose and demonstrate the functionality of a novel exoskeleton which provides variable resistance training for human hands. It is intended for people who suffer from diminished hand strength and low dexterity due to non-severe forms of neuropathy or other ailments. A new variable-stiffness mechanism is designed based on the concept of aligning three different sized springs to produce four different levels of stiffness, for variable kinesthetic feedback during an exercise. Moreover, the design incorporates an interactive computer game and a flexible sensor-based glove that motivates the patients to use the exoskeleton. The patients can exercise their hands by playing the game and see their progress recorded from the glove for further motivation. Thus the rehabilitation training will be consistent and the patients will re-learn proper hand function through neuroplasticity. The developed exoskeleton is intrinsically safe when compared with active exoskeleton systems since the applied compliance provides only passive resistance. The design is also comparatively lighter than literature designs and commercial platforms.**

***Index Terms*—automatic variable stiffness, hand rehabilitation, virtual reality, tele-rehabilitation**

I. Introduction

Limited hand movement and loss of independence is a common struggle for patients that suffer from injuries and disorders such as spinal cord injury, traumatic brain injury, peripheral neuropathy, hemiplegia as well as predicaments caused by age. 795,000 new patients suffer strokes every year in America and 1.1 million in Europe [1]. The percentage of the population aged 65 and older is projected to increase significantly in the coming years [1]. In addition, the affected population is not limited to the elderly. Out of the 270,000 people in the US with spinal cord injury, most are young men with a peak age of 19. The demographic with incomplete tetraplegia has reduced hand mobility but good potential for recovery through proper rehabilitation training [2]. This demands an urgent need for more effective and efficient approaches to rehabilitation. As the 21st century continues to advance in “robotics” and “smart homes,” rehabilitation robotics has the potential to meet the demand for low-cost therapy for both the aging and young population. It can offer motor skill practice as well as provide variable intensity training on an as-needed basis while reducing the dependency on the physiotherapist's assistance, this is due to the remote access provided to the physiotherapist via the Database embedded within the system [3].

Neuroplasticity is the brain's ability to reorganize itself by forming new neural connections, allowing the nerve cells in the brain to compensate for injury. This implies that through persistent training, people with impaired hand motion can re-learn proper hand function [4]. Various studies have shown that highly repetitive and consistent movements are key to effective stroke rehabilitation [5], [6]. However, patients often lose motivation to continue with repetitive and boring exercises, thus negatively impacting their progress [7]. Hence, the rehabilitation should involve means of motivation to ensure consistency in their training, as consistency is key for effective neuroplasticity.

Loaded exercises associated with task-oriented training help in the recovery of upper-limb function [8]. Resistance exercises have shown to improve muscle strength of stroke patients [9]. In addition, introduction of interactive games in rehabilitation has shown to improve user motivation, thereby, continuing rehabilitative exercises [7]. Game design and visual display of progress were shown to increase motivation and engagement [10]. Hence, this work aims to provide hand rehabilitation through means of grip strength training along with a virtual environment with progress tracking for the patient.

Existing devices on the market for hand rehabilitation include MusicGlove and RAPAEL Smart Glove. The former engages the user through an engaging musical game. The user wears the glove and plays the game by making different pinching movements synced with various musical notes [11]. It aims at motivating patients and improving hand dexterity but lacks resistance or strength training. RAPAEL Smart Glove is another system like music glove in functionality with more game options, however, it too lacks strength training [12].

While, several existing force feedback systems focus on assistive rehabilitation [13], [14], this work aims to provide hand rehabilitation by means of exercise. It aims at providing grip strength training through variable stiffness to accommodate for patients with varying hand strength.

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Numerous systems, although not commercially available, are currently being developed which employ force feedback. These systems can be divided into two categories, active and passive. Active systems use servomotors, hydro pumps or pneumatic pumps to push or pull on the fingers [15]. Active systems transfer energy into the system. These systems, however, pose a safety risk in their design. For example, motor failure could lead to unwanted forces on the fingers. Furthermore, these systems are bulky and heavy and, in some cases such as the pneumatic pumps, noisy. Hence, the field of soft robotics is increasingly being explored, with a focus on shape memory alloys and artificial muscles. However, these are costly and usually difficult to manufacture [16], [17].

A passive system, on the other hand, does not input any energy directly to the system. Therefore, it is not only safer, but also requires very little, if any, energy consumption. Furthermore, a passive system is usually much lighter as it usually does not need bulky motors or servos to provide the feedback [15]. One such system is Dexmo [18], which provides passive force feedback through the use of sensors and a locking mechanism, thereby providing the sensation of grasping objects in a virtual environment. Although, this design is lightweight and passive, it does not have variable stiffness and hence cannot be used for variable strength training. The improved version of Dexmo includes variable stiffness using impedance control of servomotors but this makes the system non-passive [19].

Continuous variable stiffness actuators [20-22] and recent discrete variable stiffness joints [23-25] provide different stiffness levels, which involves tuning actuators and complex mechanisms, resulting in bulky designs. Another possible variable stiffness mechanism is the Jack Spring, a patented invention that allows for changing the stiffness by changing the number of active coils in the spring. It uses a simple method to adjust the number of coils [26]. However, changing the stiffness is slow as a number of coils have to be turned through before the change in stiffness is considerable. Furthermore, the decreasing number of active coils, as the stiffness is varied, poses a limit on the safe travel distance of the spring.

To overcome the aforementioned challenges, this work aimed to build a wearable exoskeleton hand for rehabilitation with the following three objectives: to provide variable grip strength training through variable stiffness, to engage the patient through a computer game, and to track the progress made by the patient for further motivation. All these objectives ultimately serve the purpose of developing an automatic hand rehabilitation device which requires minimal human intervention.

The proposed system provides a novel approach of providing discrete variable stiffness while still being passive and compact. Moreover, the introduction of a game ensures that the patients are kept engaged as well as motivated through progress tracking. It further aids in reducing the long-term costs and reliance on therapists by providing a system wherein the therapist can remotely monitor their patients' progress.

II. System Overview

The system, designed to give mobility and strength training to patients, consists of three sub-systems; the mechanical exoskeleton, the electrical system, and software system.

The mechanical exoskeleton system consists of two main parts, as shown in Fig. 1, the variable stiffness mechanism, and the force transmission system, which transmits the force from the springs to the fingers. The electrical and software systems include sensors to record finger movement, a microcontroller and an interactive game. The microcontroller connects the mechanical system to the software system (game) through linear actuators and sends data from the sensors mounted on the fingers to the game. This configuration is made clearer in Fig. 2.

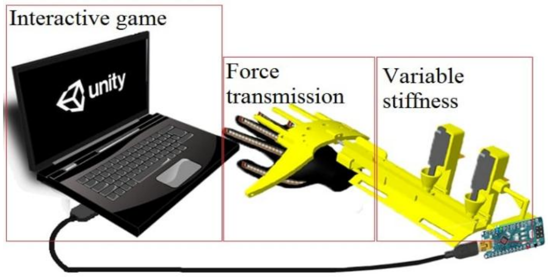


Figure 1. System design

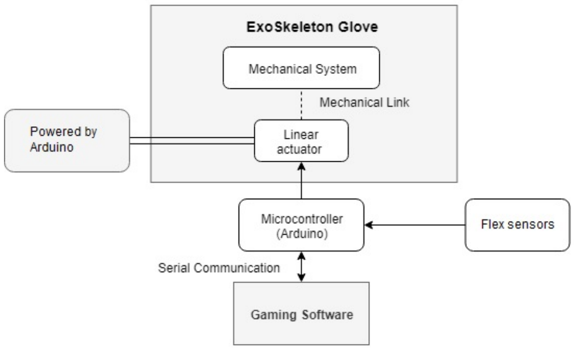


Figure 2. Block diagram

A. Variable Stiffness Mechanism

The novel variable stiffness mechanism consists of three custom-made extension springs, two linear actuators, the forearm-mount, and the slider mechanism as shown above in Fig. 1. The forearm-mount was designed to fit on the forearm while housing the springs, the linear actuators and the sliders. The three springs each have a decreasing diameter, so they all fit inside one another. On one end of the springs are loops while at the other end there are extended hooks of different lengths corresponding to their diameter and their position within the 3-spring system. The outermost spring has the longest hook length and is fixed in place. The stiffness of other springs appends onto this base stiffness level when they are engaged. The other two springs have their hooks attached to sliders so that can move freely. Different springs are selected by locking the different sliders in place using linear actuators.

B. Force Transmission System

In order to transmit the force from the springs to the fingers, braided fishing lines were used. A Bowden system was used to transfer force to the thumb. A taut-line hitch was used in order to keep tension in the cable, especially when different users with different hand measurements utilize the device.

C. Hand Motion Capture

The exoskeleton is designed to provide grip strength and mobility training. A survey of commonly used exercises for such training was performed and the power grip gesture was chosen as it is suitable for the purpose of this project. Fig. 3 illustrates the various rehabilitation exercises commonly suggested by physiotherapists [27].

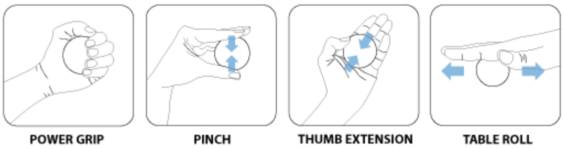


Figure 3. Various hand rehabilitation exercises

In order to play the game, the user's hand movements need to be recorded as they perform the gripping gesture. The gesture should trigger an action in the game to allow the user to play the game. For gesture tracking, several options were explored such as accelerometers, optical tracking, leap motion and flex sensors. Flex sensors, which are sensors whose resistance varies as they are bent (Fig. 4 [28]), were chosen as the input sensor keeping the end user in mind, as they do not impede the natural motion of the hand, are comfortable and lightweight. They can also be used to estimate the patient's ability to flex their fingers over time. These sensors were measured to be around 115 mm in length which is longer than the length of an average human finger [29]. Given its length, the sensors are suitable for accommodating a variety of different hand sizes.

Figure 4. Flex sensor

D. Game Development

The game serves as an engaging alternative to traditional rehabilitation. The patient uses the griping motion to play the game, where the ball displayed in Fig. 5 is moved within the game depending on how clenched the user's hand is. The variable stiffness levels of the spring mechanism correspond to different levels within the game. Depending on the patient's progress, a new level is unlocked automatically.

In the game, the ball must hit the tile coming its way to score points. The user can, therefore, bend their fingers to move the ball left or right to hit the tile and score points.

Figure 5. Rehabilitation game

The amount by which the user has to bend their hand in order to jump from one tile to another can be adjusted to accommodate for users who have low mobility, making the game more sensitive to their movements.

E. Progress Measurement

Clinically the patient's mobility, dexterity, and grip strength are measured through tests requiring human intervention or through devices such as the dynamometer which cannot be incorporated to record the patient's progress simultaneously as they play the game. For this reason, the flex sensors were used to develop an automatic method of progress tracking which tracks the patient's flexion capability while they play the game.

The progress of the user is based on their ability to bend their fingers. The user and therapist can view the daily and weekly progress. The weekly progress is calculated by averaging the daily progress of seven consecutive days. Bar graphs and radar charts are used to display weekly and daily progress.

In order to store the progress of the patient and provide daily and monthly reports, the data should be saved for accessing when needed. MySQL database was chosen for this purpose and the database was configured such that it allows the therapist remote access to the patient's data. This functionality allows for the device to be used at home, thus potentially saving costs and resources associated with traditional one to one therapy.

F. Overall Physical System

Fig. 6 below shows the complete implemented physical system.

Figure 6. Complete Physical system

III. Theoretical Model

A. *Working Principle of The Variable Stiffness Mechanism*

The design criteria established to develop the variable stiffness mechanism capable of transmitting a variable force to the patient's fingers involved consideration of ease of adjustability of stiffness levels, while minimizing size, weight and electrical components. These criteria were emphasized since the patient's health is the main priority. The chosen design is a novel method of passive variable stiffness, stemming from springs in a parallel configuration. The system consists of three springs with different stiffness constants placed inside one another as shown in Fig. 7, and linear actuators to activate those springs.

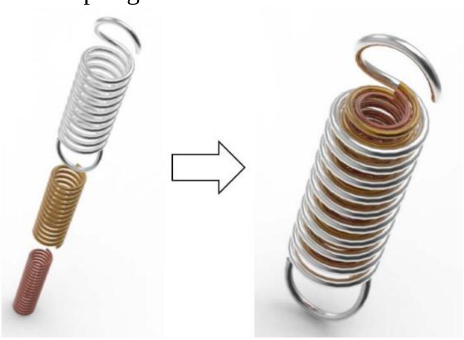


Figure 7. Springs design rendering

The configuration is set up such that the springs are connected to the hand on one end and to sliders on the other end as shown in Fig. 8 (a)-(d). The connections to the hand are guided by a cable routing mechanism. The stiffness experienced by the fingers is based on the number of springs activated. In the diagrams shown below, the four possible stiffness levels are illustrated. An engaged spring is represented by a solid line meanwhile a disengaged spring is represented by the dashed line. It engages either when the hook of the spring (line connecting the springs to the cylinders on the right) is latched onto a rigid pole or when a slider is locked by the linear actuator.

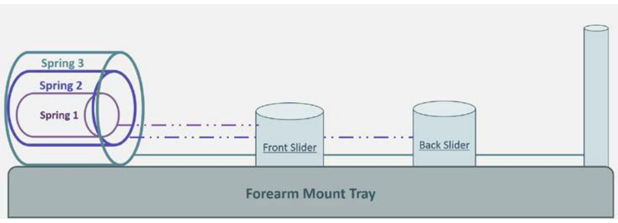


Figure 8 (a). Variable stiffness illustration mode 1

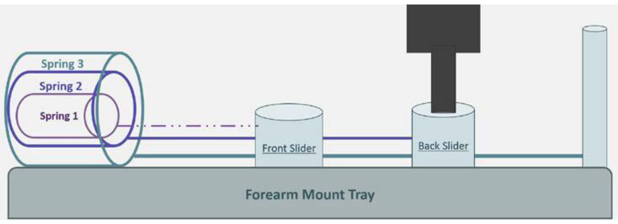


Figure 8 (b). Variable stiffness illustration mode 2

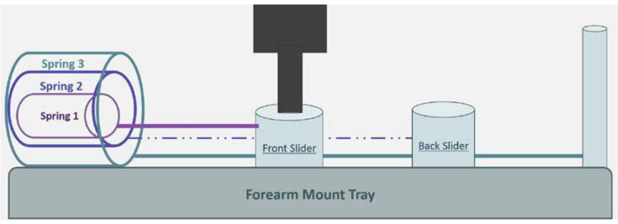


Figure 8 (c). Variable stiffness illustration mode 3

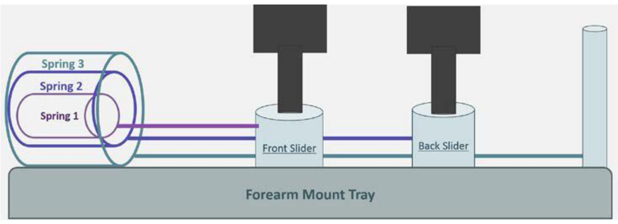


Figure 8 (d). Variable stiffness illustration mode 4

An active spring connection simply means that the cables routed to the fingers will be restrained by the active spring, hence the higher the number of springs activated the higher the resistive force felt by the fingers. The linear actuators that help engage springs 1 and 2 are controlled by the microcontroller which receives the signal from the game software. Hence, the selection of the springs and in turn the stiffness is changed automatically. The various stiffness modes are outlined in Table I below.

TABLE I. Modes of Operation for Variable Stiffness

Modes	Linear Actuators Activated	Active Springs	Equivalent Stiffness
Mode 1	None	Spring 3	K3
Mode 2	Back	Spring 3 + Spring 2	K3 + K2
Mode 3	Front	Spring 3 + Spring 1	K3 + K1
Mode 4	Both	All springs	K3 + K2+ K1

B. *Spring Constant Assumptions*

In order to choose the springs capable of providing adequate resistance to the fingers for this design, an approximation of the resistance the patient could endure had to be made. The maximum force coming from the springs were approximated from a research on hand grip strength of unaffected hands of hemiplegic patients, as the unaffected hands are still low in mobility and dexterity in comparison to healthy people and can be good candidates for strength and mobility training [30]. The spring dimensions' calculations were made using Hooke's Law. The resulting springs are shown in Tab. II below. Material was taken to be stainless steel 17-7 ASTM A313 for all springs.

TABLE II. SPRING PROPERTIES

Set 1	Wire Diameter (mm)	Outer diameter (mm)	Length Inside Hooks (mm)	Extended Hook 1 (mm)	Extended Hook 2 (mm)	Spring constant (N/mm)
Spring 1	0.75	10	70	15	45	0.31
Spring 2	1.1	15	70	15	30	0.23
Spring 3	1.25	20	70	15	0.15	0.11

C. *Data Glove*

Five 4.5" flex sensors were mounted onto a glove, one for each finger, along with a voltage divider circuit. This would enable the measurement of flexion for each finger using a single flex sensor. A single flex sensor was used for each finger to maximize cost, weight and resource efficiency. The data glove can be seen in Fig. 9.

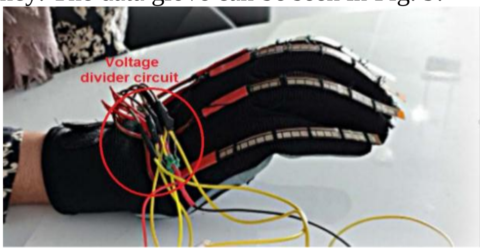


Figure 9. Data glove with Flex sensors

D. *Flex Sensor Mapping*

Mapping the flex sensor readings adequately is important as the flex sensors estimate the progress of the patient, in addition to tracking finger movement. The relationship between the resistance and the flexion of the flex sensors is non-linear. Hence, the relationship between the resistance and flexion was developed manually by recording the resistance at various intervals of bending diameter "D" as the flex sensors were gradually flexed from a fixed pivot, as shown in the Fig. 10.

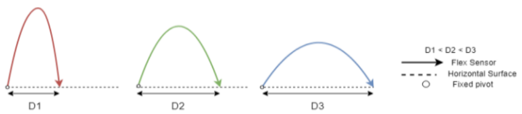


Figure 10. Flex sensor mapping procedure

This process was repeated several times and an average was taken. The graph in Fig. 11 shows the relationship developed

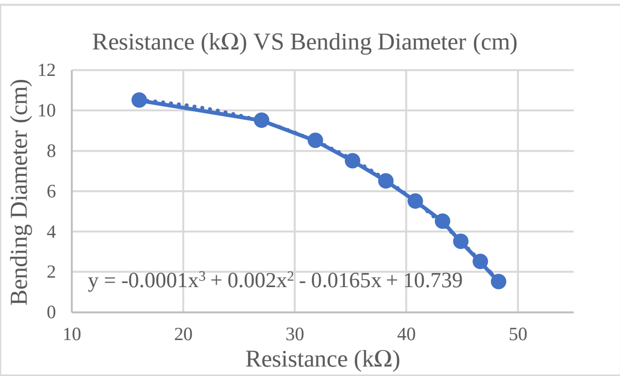


Figure 11. Flex sensor mapping graph

The theoretical model developed for the flex sensor mapping was validated by wearing the glove and repeating the same experiment for mapping the flex sensors as described earlier. This was done only 2 times and an average was taken. The graph in Fig. 12 was obtained.

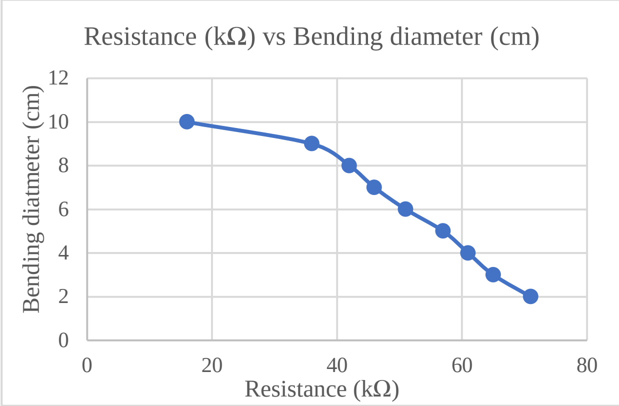


Figure 12. Flex sensor mapping graph with the flex sensors worn

The obtained graph follows a similar trend as to the one obtained with the flex sensor not worn by a user. Hence, the relationship between the bending diameter and the resistance was approximated by model developed earlier.

The model adopted has a few other assumptions. It assumes that the user bends their fingers each time in a similar method to the experimental method. Additionally, it assumes that the mapping is one to one and the sensors would give the same reading for each bending diameter regardless of how it bent to obtain the same bending diameter.

E. *Flex Sensor Calibration*

In order to relate the flex sensor readings to the clenching of the hand, the sensors were calibrated using average readings for several users who were asked to clench their and open their hands 10 times successively. Readings were recorded at fully open and fully clenched positions. Note here that the users had different hand sizes which would impact the calibration, hence a mean of all the users was taken to obtain an average measurement. The flex sensor readings were calibrated to vary from zero for fully open hand to 100% for fully clenched hand of an average healthy human. Tab. III below shows the data obtained to calibrate the flex sensors.

TABLE III. DATA USED FOR CALIBRATING FLEX SENSORS

Test Subject	Average value for each flex sensor upon fully clenched hand				
	Thumb	Index	Middle	Ring	Pinky
1	930	532	901	864	678
2	892	560	887	892	582
3	951	613	945	917	724
4	943	546	921	909	625
5	923	596	929	912	632
Mean	928	569	917	899	648

F. Progress Calculation

Fig. 13 below shows how the flex sensor readings might be varying during the game with time. Top 20% of all the readings obtained when the user plays the game are averaged to reduced anomalies, in order determine the user’s bending ability.

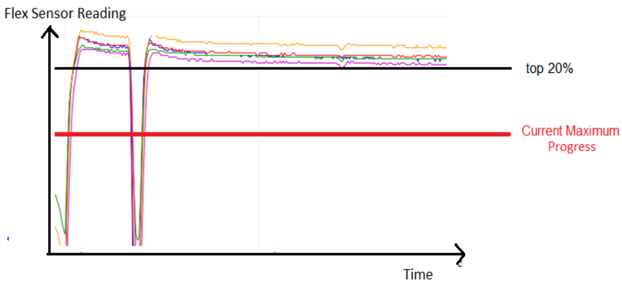


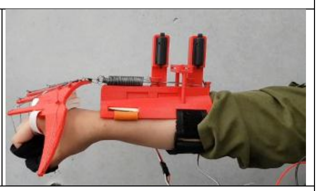
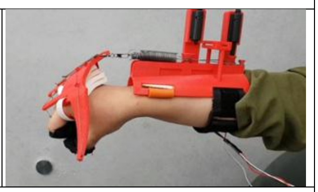
Figure 13. Flex sensor readings

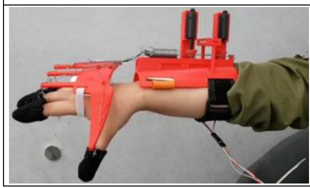
IV. Experimental Tests and Results

A. The Mechanical System

Initially, a simple prototype was developed to simulate the mechanical system’s response to the computer's prompts, via the linear actuators. This was achieved by attaching the 3D printed actuator compartment to the forearm mount with a spring holder. After printing, the nested springs and linear actuators and tested for various modes of operation as shown in Tab. IV. When testing this configuration, it was found that the locking of a spring with the linear actuator does indeed change the force experienced by the hand. The prototype was modified several times in order to improve the activation of the springs, the friction in the slider and the transmission of force from the springs to the fingers. In addition, the Arduino was connected to the computer game to evaluate the response of the system to signals received from the game. The signals from the game were successfully transferred to the actuators, which functioned as expected.

TABLE IV. Testing Stiffness Levels

Relaxed Position	Clenched Position
Mode 1	
	
Mode 2	
	
Mode 3	

Relaxed Position	Clenched Position
	

To further test the system’s ability to provide different stiffness levels, another set of springs were used with the dimensions and spring constants shown in Tab. V. where the stiffest spring is 13 times the stiffness of the least stiff spring, giving a wide range for achievable stiffness levels. Fig. 14 shows the springs being tested for determination of the spring constant.

TABLE V. Spring Dimensions and Constants

Set 2	Wire Diameter	Outer Diameter	Body Length	Spring Constant
Spring 1	0.8mm	5mm	35mm	0.39 N/mm
Spring 2	0.8mm	10mm	35mm	0.12 N/mm
Spring 3	0.8mm	15mm	35mm	0.03 N/mm

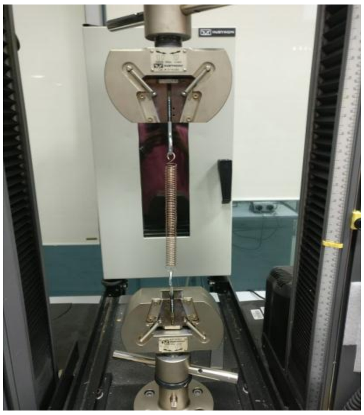


Figure 14. Spring constant testing

Table VI below shows the achievable stiffness levels using the springs from Table V, where the difference from the lowest and highest possible stiffness level is 18 times.

TABLE VI. Achievable Stiffness Levels

Modes	Active Springs	Equivalent Stiffness	Equivalent Stiffness (N/mm)
Mode 1	Spring 3	K3	0.03 N/mm
Mode 2	Spring 3 + Spring 2	K3 + K2	0.15 N/mm
Mode 3	Spring 3 + Spring 1	K3 + K1	0.41 N/mm
Mode 4	All springs	K3 + K2+ K1	0.54 N/mm

Additional stiffness levels would also be achievable if a third linear actuator is implemented. However, this results in a trade-off between the size, cost and weight of the system, where the length of the system exceeds the forearm length of the patient and the overall design becomes less favorable for commercial purposes.

After the final rendering of the prototype was complete, along with the springs' dimensions, positions and specifications, the mechanism was printed, assembled and tested to ensure safety. Safety was tested by extending the springs to lengths far beyond their typical operational length, to simulate scenarios such as the hook tangling with an object and being pulled hastily. The springs were also loaded and unloaded rapidly and continuously to mimic fatigue, as the design of the prototype did not allow it to undergo normal fatigue tests, and testing the springs individually would not testify to their fatigue when in the parallel configuration. Apart from the springs, the 3D printed parts had undergone thorough testing for material strength, some printed parts failed the test and were re-printed using a higher infill density and tested once more. The comfort of the system was also evaluated. To assess the comfort a random group of test subjects were chosen to wear the device and play the game, later they were asked to rate how comfortable the system was on their hand. After the feedback, the hand mount and wrist mount were both re-designed to be more ergonomic. Different Velcro and foam options were also investigated, and high-quality memory foam was used in the final prototype.

B. *Testing the Game*

Flex sensors were used as an input by mounting them on top of a glove. This method was employed so that the sensors bend with the natural curve of the fingers, thereby, changing its resistance and triggering an action within the game.

The game developed was tested in combination with the flex sensors. Fig. 15 shows how the horizontal position of the ball changes depending on how much the flex sensors are bent.

Figure 15. Various hand positions displace the ball horizontally, between left, center and right positions

The software was tested for functionality to ensure all requirement specifications were met. In addition, non-functional testing, for usability and efficiency, was also carried out. Accessibility and usability of the software was tested by evaluating ease of navigation by test subjects of varying age groups. Subjects were able to comprehend the gameplay the game within approximately 10 tries. Feedback obtained from users, and data gathered was used to improve the software, as necessary.

C. *Testing the Progress Tracking Method*

The progress of the user was tracked using the flex sensors. Fig. 16 shows results for the progress for each finger from two different games, one where the hand was flexed less and the other where it was flexed more.

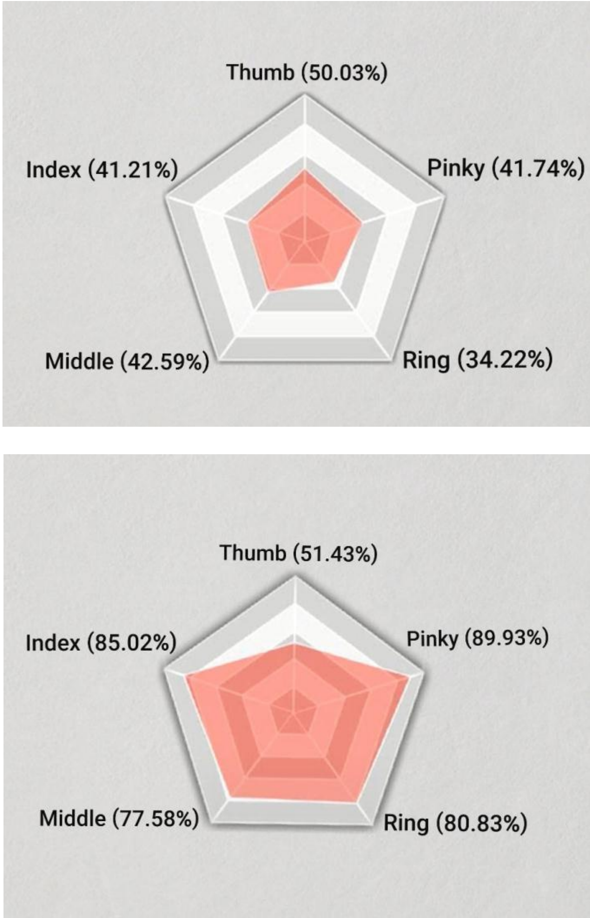


Figure 16. Results for Maximum flexion for each finger measured in comparison to a healthy human hand, where the fingers are flex more (bottom) and the fingers are flexed less (top)

It is evident that the program developed was able to provide an estimate of flexion for each of the fingers. The case where the fingers were bent more, a higher reading was obtained as expected.

In order to further test the implemented progress tracking, the system was tested on a group of five healthy test subjects. The subjects chosen had varying hand sizes. The subject was made to wear the flex-sensor embedded glove without the stiffness mechanism. The purpose of the test was to see if reasonable information regarding the range of motion of the test subject is obtained using the software. Since the test subjects are all healthy humans, the range of motion calculated for each of the fingers is expected to be in close proximity of or equal to 100%.

The test was done as follows: First the user was asked to wear the glove. Next, the user was asked to make a complete fist 10 times. An average maximum flexion obtained over 10 trials was then calculated.

TABLE VII. TEST RESULTS FOR PROGRESS TRACKING ON HEALTHY HUMAN HANDS

Test Subject	Average value obtained for each flex sensor upon fully clenched hand in comparison to a healthy human				
	Thumb	Index	Middle	Ring	Pinky
1	34.2%	100.0%	98.7%	97.3%	99.1%
2	45.5%	94.4%	95.8%	94.7%	97.1%
3	23.3%	93.6%	92.1%	87.9%	85.4%
4	56.1%	100.0%	100.0%	98.4%	100.0%
5	42.9%	95.7%	93.6%	89.5%	94.3%
Mean	40.4%	96.7%	96.0%	93.6%	95.2%

It can be observed from Tab. VII above that the range of motion obtained for all fingers, apart from the thumb is within a 15% difference from the expected value of 100%, even though a range of hand sizes was considered. Hence, the system is able to estimate the flexion capability of a wide range of users. The flexion achieved for the thumb, however, was about 60% lower than the expected value in most cases. This difference is because the fist gesture can be made in several different ways, which does not require bending the thumb to its fullest capability, so the result is as expected.

The model developed is a preliminary one for estimating the flexion capability of the patient automatically, as the user plays the game, with minimal human intervention. It can be refined further through gathering more data from several users to map and calibrate the sensors, and calibrating based on hand size and gender to test the repeatability and reliability of the results.

G. Weight Comparison

The developed system was evaluated by comparing the weight of the overall system to other existing systems. Tab. VIII. below shows that the system developed is lighter than similar existing systems. It should be noted that the proposed system distributes the quoted weight across the hand and the forearm. This implies that the weight imposed on the hand itself, unlike other systems, is even smaller.

TABLE VIII. WEIGHT COMPARISON WITH OTHER VARIABLE STIFFNESS KINESTHETIC GLOVES

Systems	Weight (g)
CyberGrasp [5]	450
Dexmo [5]	270
FFHG [5]	310
HEXOSYS [5]	400
Proposed System	266

Overall, the system developed was validated to be functional. The next step is to test the proposed system with actual patients to evaluate the suitability of the system for meeting rehabilitation needs.

V. CONCLUSION

A novel variable stiffness mechanism that is compact, lightweight, and cost effective when compared to other existing mechanisms was developed. In addition, a preliminary continuous progress tracking method is also devised which successfully estimates the flexion capability of each individual finger. The variable stiffness mechanism produced shows potential in the medical industry as a rehabilitation device as well as various other applications that require low energy consumption discrete levels of stiffness change. It can also potentially be used in wearable robotics and haptics. Furthermore, the integration of the developed automatic variable stiffness mechanism into a game-based exoskeleton opens avenue for remote at-home rehabilitation in addition to usage in medical clinics for rehabilitation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors made substantial contributions to literature review and acquisition of data.

WA and NF were involved in the design and development of variable stiffness mechanism and the 3D printed exoskeleton. HT also made contribution within this scope. HT and NR conducted research on games and its potential within the scope of this project. Both authors participated in the design and development of the game and performed analysis on user progress data, in addition to making this data remotely accessible.

All authors were involved in the drafting of the manuscript. All authors had approved the final version.

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