HandMATE: Wearable Robotic Hand Exoskeleton and Integrated Android App for At Home Stroke Rehabilitation

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Abstract— **We have developed HandMATE (Hand Movement Assisting Therapy Exoskeleton); a wearable motorized hand exoskeleton for home-based movement therapy following stroke. Each finger and the thumb is powered by a linear actuator which provides flexion and extension assistance. Force sensitive resistors integrated into the design measure grasp and extension initiation force. An assistive therapy mode is based on an admittance control strategy. We evaluated our control system via subject and bench testing. Errors during a grip force tracking task while using the HandMATE were minimal (<1%) and comparable to unassisted healthy hand performance. We also outline a dedicated app we have developed for optimal use of HandMATE at home. The exoskeleton communicates wirelessly with an Android tablet which features guided exercises, therapeutic games and performance feedback. We surveyed 5 chronic stroke patients who used the HandMATE device to further evaluate our system, receiving positive feedback on the exoskeleton and integrated app.**

I. INTRODUCTION

Stroke is the leading cause of severe long-term disability in the US [1]. The probability of regaining functional use of the impaired upper extremity is low [2]. At 6 months post stroke, 62% of survivors failed to achieve some dexterity [3]. Such impairments can inhibit the individual's ability to perform activities of daily living (ADL). Subsequently, upper limb rehabilitation recovery to improve ADL is one of the main self-reported goals of stroke survivors [4].

Outpatient rehabilitation is recommended for survivors that have been discharged from inpatient rehabilitative services [5]. However, outpatient rehabilitation in general is largely underutilized, with only 35.5% of stroke survivors using services [6]. Factors inhibiting outpatient therapy include cost, lack of resources and transportation. Wearable robotics that enable home-based therapy have the potential to overcome these barriers. They provide assistive movement forces which enable task-specific training in real-life situations that patients are often unable to practice without a clinician. See [7] for wearable hand robots for rehabilitation review.

At home therapy is not without its limitations. The inability to motivate oneself and fatigue are the most common reported factors resulting in failure to adhere to home based exercise programs for stroke recovery [8]. While wearable robotics can reduce fatigue during exercise, it does not directly address lack of motivation. Research has shown incorporating games into home therapy can encourage compliance [9]. Zondervan *et al.* showed that use of an instrumented sensor glove, named the MusicGlove, improved self-reported use and quality of movement, greater than convention at home exercises [9]. Other studies showed increased motivation to complete the therapeutic exercises and optimized movement when the user is given feedback of their performance via the Microsoft Kinect [10]. Wearable robotic systems that offer feedback and gaming capability may optimize at home stroke therapy.

Such a system was presented by Nijenhuis *et al.* in which stroke survivors showed motor improvements after completing a 6 week self-administered training program comprised of a dynamic hand orthosis and gaming environment [11]. However, the hand device was passive, assisting only with extension, which limits the range of stroke survivors who could utilize such a system. Research groups have proposed combining their powered take-home wearable hand devices with custom integrated gaming systems [12], or guided exercises [13]; however, they have yet to conduct clinical trials. Notably, Ghassemi *et al.,* have developed an integrated multi-user VR system to use with their X-Glove actuated orthosis, which will allow for client-therapist sessions without the patient having to travel [12].

Tablets are relatively inexpensive, portable, and straight forward to use, with 47% of internet users globally already owning one [14]. Furthermore, a recent study demonstrated the success of a tablet based at home exercise program in improving the recovery of stroke survivors [15]. Notably, the study evaluated the accessibility of tablets, concluding every participant used the tablet successfully. Therefore a wearable powered hand robot with a dedicated tablet app which will

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provide functional games, task-specific guided exercises and feedback of movement, could optimize at home stroke therapy.

II. AIMS

The goal of this project was to create a wearable robotic exoskeleton that enables repetitive practice of task-specific and goal orientated movements, which translates into improvements in ADL. Furthermore, for maximum use and successful integration into home-based rehabilitation, we aimed to create an Android application compatible with the robotic exoskeleton.

To meet these goals, the following design objectives were established: 1) Assistance with finger flex/extension. 2) Assistance with thumb carpometacarpal (CMC) add/abduction and thumb metacarpophalangeal (MCP) flex/extension. 3) Independent assistive control of each finger and thumb. 4) Portable for at home use, meaning the device has to be lightweight and wireless. 5) Relatively affordable. 6) Integrated with android tablet app. Specific design goals for the app included: 1) Easy to use. 2) Allow the user to control the exoskeletons assistance mode through the app. 3) Records the user's data and prompts the user via notifications to complete the allocated daily or weekly recommended activity time.

In this paper we will evaluate if the proposed device and app goals have been achieved via bench and subject testing.

III. DESIGN

The HandMATE device (Fig. 1) builds upon the Hand Spring Operated Movement Enhancer (HandSOME) devices [16, 17, 18]. The HandSOME devices are non-motorized wearable exoskeletons that assists stroke patients with finger and thumb extension movements. The HandSOME I device assists with gross whole hand opening movements, while the HandSOME II assists isolated extension movement of 15 finger and thumb degrees of freedom (DOF), allowing performance of various grip patterns used in ADL. While both devices have been shown to significantly increase range of motion (ROM) and functional ability in chronic stroke subjects [16,18], the HandSOME devices only assist with extension movements and require enough flexion activity to overcome the assistance of the extension springs. As many stroke patients also suffer finger and thumb flexion weakness, we decided to build upon the work of the high DOF HandSOME II and additionally utilize power actuation so we can assist with both flexion and extension movements.

Figure 1: HandMATE device. Individually actuated fingers and thumb shown. Electronics box is affixed to back of splint.

A. Mechanical

The design assumes the distal interphalangeal (DIP), proximal interphalangeal (PIP), and finger metacarpophalangeal (MCP) joints are all 1 degree of freedom (DOF) rotatory joints. We utilize the linkage system described in the HandSOME II [20] for the fingers. The linkage forms a parallelogram (Fig. 2), ensuring attachment points move in a circular trajectory about the center of rotation of the human joint. The additional links prevent the distal attachment point from sliding along the skin and ensures the finger pads also travel in the same circular trajectory around the center of rotation while maintaining perfect alignment with the human segment. This design allows components to be placed on the back of the finger and hand, permitting individual assistance for each finger without obstruction, while still achieving an identical applied force direction to traditional exoskeleton designs that rely on aligning the exoskeleton DOF with the human DOF, which is not possible for many joints in the hand.

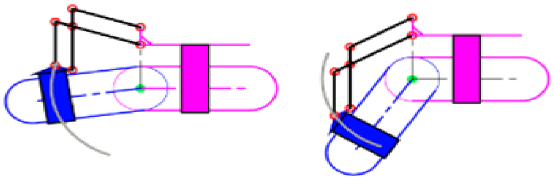

Figure 2: Finger parallelogram linkage with additional distal link, shown during extension (left) and flexion (right). Adapted from [16].

Despite the highly dexterous properties of the human hand, previous studies show manipulation tasks are dominated by a smaller number of effective degrees of freedom [19]. This has been successfully integrated into exoskeleton designs where several grasping patterns can be achieved by coupling finger DOF, which reduces the number of motors needed [20]. In contrast to the HandSOME II, our design utilizes this under actuation technique by coupling the MCP and PIP joints in the fingers. The linkage has been designed to allow 90° ROM at the MP and 100° at the PIP, a rotation ratio of roughly 1:1.1, which is within ROM required to complete ADL [21]. Additionally, we can assist with DIP movement by adding another segment to the device (Fig. 3). The DIP section is elastic actuated so additional motors and weight is not added to the design. The additional distal segment will be user dependent and avoided when possible to reduce disruptions to tactile feedback from the finger tips when grasping objects.

Figure 3: Additional proximal finger segment with passive elastic assistance.

The thumb design aligns the exoskeleton DOF with the human DOF, specifically at the CMC and IP joints. The CMC and MCP joint motion are combined via a 3d printed splint. This CMC/MCP splint is power actuated, while the IP joint is elastically actuated. This thumb design differs significantly from the HandSOME II design to reduce the number of actuators needed for the thumb. The end result is a lower profile design. The device does not allow for any other finger or thumb motions.

All components of HandMATE are 3d printed. Subsequently, every part is easily customizable to the patients hand dimensions for optimum fit. The material used is Markforged Onyx (Markforged, Watertown,MA, USA) ; a thermoplastic with chopped carbon fiber making it 4 times stronger than common thermoplastics such as acrylonitrile butadiene styrene. The finger and thumb attach onto a customized, 3d printed splint. This splint has a fixed 15 degree extension at the wrist to replicate more natural wrist movement when reaching for objects. The total weight of the device with motors and electronics is 340 g.

B. Actuation/Control Unit

HandMATE's system components are displayed in Fig. 5. This section will detail the components and control algorithms.

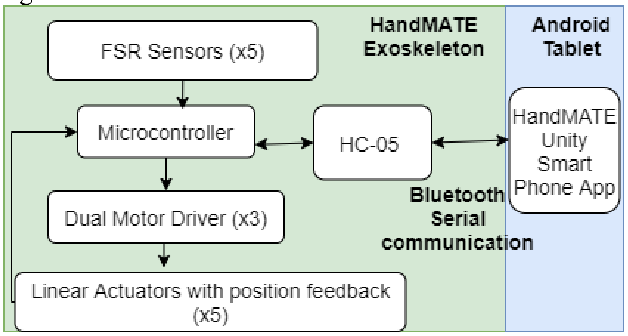

Figure 5: HandMATE system hardware components.

1) Motors

One linear actuator was used for each finger and thumb to achieve independent flex/extension. To meet design goal 5 (portability), we used the Actuonix (Saanichton, BC Canada) PQ12 linear actuator (due to their small size and weight (15g). We chose the 100:1 gear ratio option which provided 50N of peak force and 10mm/s peak speed. With our design, this allowed full ROM to be completed in under 2 seconds (fully open to close and vice versa). The PQ12 model we used has an internal potentiometer providing continuous positional feedback. With this feature, digit position is known by computing individual joint angles from the linear actuators stroke position. The 2200 mAhr batteries we selected power the device and all 5 linear actuators for 2 hours while in continuous movement mode.

2) Control Algorithm

The HandMATE device is controlled via user input from the custom Android app. This is achieved via a Teensy 3.6 microcontroller which communicates with the android smart device via a HC-05 (JY-MCU) Bluetooth serial module.

The HandMATE operating system is a finite state machine. Fig. 6, demonstrates how user input on the app is transformed to movement output by the components that comprise HandMATE.

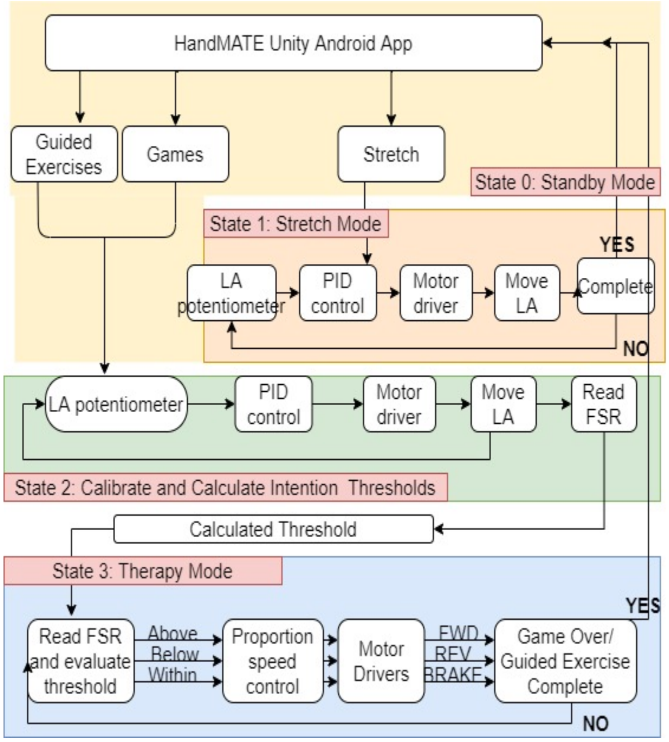

Figure 6: HandMATE state machine

HandMATE has two control modes: "stretch" and "therapy" mode. During stretch mode user can remain passive, and the device will take the user through full flexion and extension. This mode has been designed to stretch the users hand through full ROM, which has been shown to improve task performance [22]. Within stretch mode, the user can select how many repetitions to complete via the app.

Therapy mode provides assistance to the patients but requires active movement initiation unlike stretch mode where user can remain passive. This control mode is achieved via inexpensive (<5 USD) Force Sensitive Resistors (FSR) embedded within HandMATE that measures intention to flex or extend. Each finger and thumb has its own FSR, allowing independent digit control which supports several grasps and task-specific training. We utilize admittance control where initiating flexion increases the FSR reading and terminating flexion or initiating extension decreases the FSR reading (Fig. 7). To control the linear actuators movement we implemented an upper and lower FSR threshold technique, where FSR reading above the upper threshold results in flexion movement velocity proportional to the difference between the FSR reading and the upper threshold, and FRS reading below the lower threshold results in extension movement using a similar control strategy. If FSR reading is within the dead band of the upper and lower threshold the device will remain in the current position. We also use the FSR value to implement proportional speed control of the linear actuators. While FSRs can have drift and calibration changes over time, HandMATE performs a calibration before each session and thresholds in the controller can be easily adjusted manually based on patient performance. Replacing FSRs requires minor disassembly.

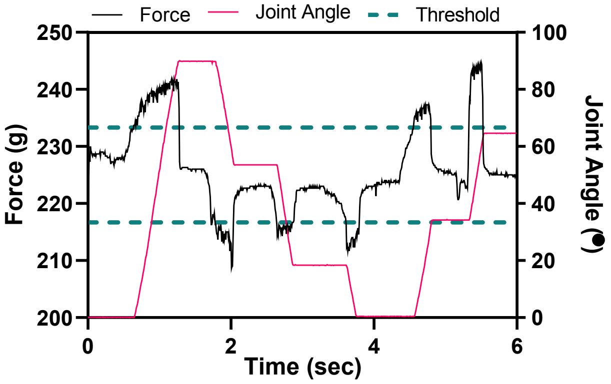

Figure 7: Left axis shows the index FSR reading, while right axis shows corresponding change in MCP joint angle over time. Dashed lines indicate upper and lower threshold. As FSR moves above or below thresholds there is corresponding movement of the digit. Graph shows HandMATE can be moved and stopped accurately at any point in the users ROM.

As this device is intended for home use, we implemented an automated calibration sequence that determines the upper and lower FSR threshold. Firstly, the user is instructed to allow the device to passively move their hand to open, close and mid position. The open and close positions are the maximum comfortable movement the patient tolerates during initial set up and is then programmed as an electronic hard stop. In these positions the FSR reading is recorded while the user is instructed to remain relaxed for a passive reading, then actively initiate grasp and finally, actively initiate opening the hand. The calibration sequence takes 1 minute to complete. The calibration sequence is initiated by the HandMATE app prior to each guided exercise and game play, as the stroke survivor's ability to initiate grasp or release may fluctuate during a training session. We have also created a manual calibration option where the thresholds can be changed by the patient if the automated calibration procedure yielded inadequate active ROM.

3) Mobile Application

The communication between the Android app and HandMATE device is bidirectional: 1) the app sends information to the device about which mode it should be in and the calibrated threshold values of the patient, 2) the position of the linear actuators, and thus patient movement, is relayed to the app so movement data can be stored and displayed for real time feedback (Fig. 6).

The app can be used in three ways: 1) The patient can access therapist mode in which they will be guided through therapeutic exercises with performance feedback from the sensors displayed on the screen and indication if they have completed the exercise successfully, 2) The patient can access game mode, in which completing therapeutic movements like opening and closing the hand acts as a control command for a game. At present, 4 custom games have been created for the HandMATE application. 3) Progress reporting, where both users and therapist can access activity logs and track their progress. Notifications can be enabled which will prompt the user if their recommended daily usage has not been achieved.

IV. METHODS AND RESULTS

A. Device Evaluation

Ethical approval was granted by the MedStar Health Research Institute Board of Review. To test our admittance control algorithm we designed a grip force tracking task. We recruited 10 healthy subjects (mean age = 26, males = 5). Subjects were required to track a sine wave that ranged from 0 to 25% of their maximum voluntary contraction. We created a custom compliant dynamometer using a 50lb load cell (Transducer Techniques, Temecula, CA, USA). The compliance of the dynamometer required finger movement during the grasping tasks, so task performance could degrade the HandMATE controller. The HandMATE was operated in "therapy" mode. The sine wave and visual feedback of their grip force was displayed on a computer screen. Subjects completed 12 sine tracking tasks with and without the HandMATE device. The dominant hand was used for all tasks.

Table 1: Results of healthy subjects during grip force tracking task

	RMS Error (lbs)	**RMS % of 0.25MVC**
HandMATE	0.874	0.092
Without Device	0.899	0.088

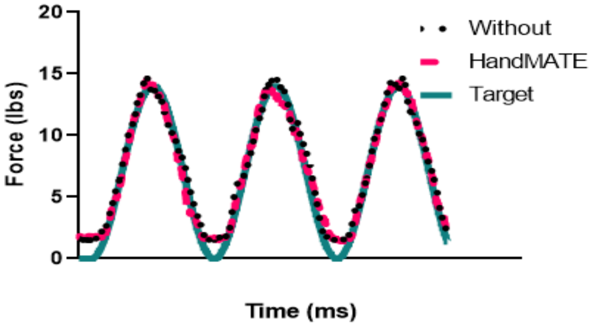

Figure 8: Mean error (lbs) of all subjects during sine tracking task

We computed their error rate (Table 1). No significant difference was found with or without device use. The results show: 1) HandMATE does not impede grip force performance as tracking error is comparable to performance without the device, and 2) our proposed admittance control, using inexpensive FSR, produced accurate control of flexion and extension movements as indicated by root mean square (RMS) of error.

Bench top testing was performed to test and quantify the performance of the device [18]. We examined the torque required to actively move the finger through the full ROM, with the device in admittance control "therapy" mode. For optimum finger and thumb movement, the device should produce minimal resistance to movement. We recorded resistance torque via a load cell (MLP 50, Transducer Techniques, Temecula, CA, USA). Results can be seen in Fig. 8. We examined "therapy" mode under the following conditions: 1) with fixed motor speed (Fig. 9), 2) with proportional speed while exerting minimum force to move the device (Fig. 10), and 3) with proportional speed moving as fast as possible (Fig. 11).

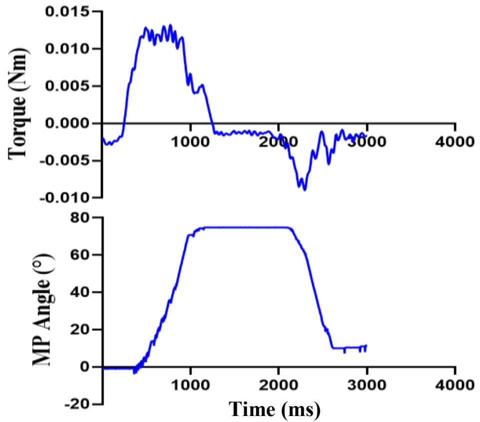

Figure 9: Top graph shows resistance toque during fixed speed movement. Bottom graph shows corresponding joint flexion/extension angle.

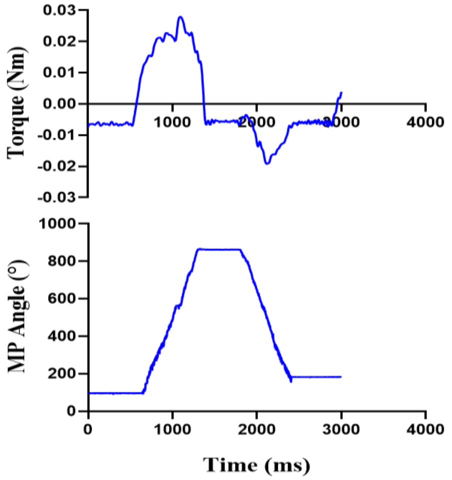

Figure 10: Top graph shows resistance torque under proportional speed controlled movement. Bottom graph shows corresponding joint flexion/extension angle

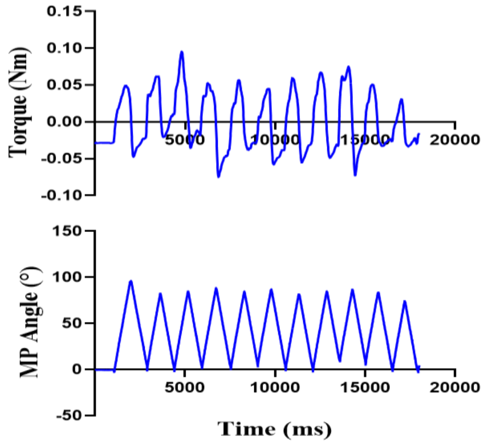

Figure 11: Resistance toque, under proportional speed controlled movement, moving as fast as possible. Bottom graph shows corresponding joint flexion/extension angle.

The resistance torque increased with speed of the movement. The peak resistance torque at fixed speed (Fig. 9) and proportional speed (Fig. 10) during cyclical movements was .013 Nm and .028 Nm. In comparison to the peak torque of .9 Nm and back drive torque of .6 Nm from the actuator, the resistance torques were accordingly 1.4% and 3.1%. A peak resistance torque of .09 Nm occurred when the device was moved as fast as possible (Fig. 11) and is 10% in comparison to the peak torque from the actuator.

B. Patient Evaluation

Five chronic stroke patients gave written consent to partake in this pilot study (age = 45 years, males =2, 3.4 years post stroke). Throughout the design and development of HandMATE we met with chronic stroke survivors with moderate to severe hand impairments. As these patients are the target users of the HandMATE system, we developed a survey to determine their needs of a home therapy system while also evaluating HandMATE. Fig. 12 shows the results of the survey.

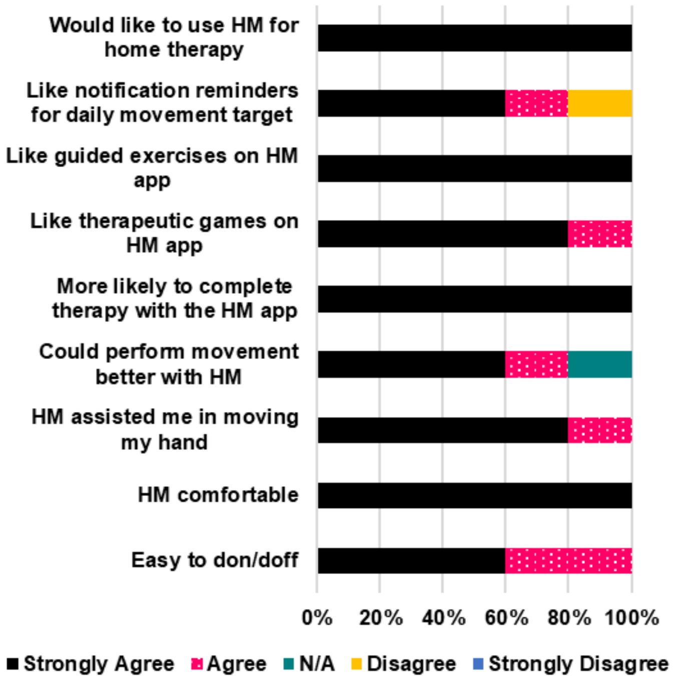

Figure 12: Survey of chronic stroke patients. HM = HandMATE.

V. DISCUSSION

We developed a wearable robotic exoskeleton that assists individual digit flexion and extension and integrated app. We demonstrated accurate control of our device via subject testing. Using embedded FSR allows for quick and automated set up of the system, and may be beneficial over EMG based or more complex systems when used at home without a clinician or a caregiver. Also increasing usability at home is made possible with control of the device via android app.

We received positive response to our proposed system by stroke survivors via survey. All subjects reported the device was comfortable to wear and the majority of subjects stated the weight of the device did not interfere with reaching. We therefore conclude we achieved our design goal of a portable system.

Future work should now include a kinematic comparison of stroke patients hand function with and without the device. We opted for a rigid design for optimal control of kinematics, specifically for stroke patients with high tone. While a rigid design is less compact than designs based on soft robotics, the forces can be applied precisely, orthogonal to the finger for optimal comfort. Prior to clinical trials, we will work on making the links on the back of the hand more aesthetically pleasing and compact as possible while maintaining appropriate kinematics.

VI. CONCLUSION

In this work, we presented a wearable hand exoskeleton, HandMATE, designed for at home stroke rehabilitation. We evaluated the control algorithm via subject testing concluding that users are able to control flexion and extension movement accurately. Moreover, we introduced an integrated android app that can be used to control the device and also provide interactive therapy or therapeutic gaming. Our previous clinical testing with the passive home-based hand exoskeleton (HandSOME) has shown that many stroke patients will comply with daily use of these devices at home with clear benefits in some subjects [16]. However, the inability to adapt the assistance levels to rapid changes in patient performance due to tone or fatigue is a disadvantage of purely spring-powered devices. HandMATE can overcome this problem by automatically adapting the force thresholds for movement in active assistive therapy mode. HandMATE can also perform passive ROM stretching exercises and assist with grasping force in severely weak patients. Finally, positive feedback from patients regarding the app and therapeutic games, suggest a positive incorporation of the system for home hand therapy.

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