https://doi.org/10.26599/AIR.2024.9150041 CAAI Artificial Intelligence Research

Enhancing Hand Rehabilitation Through Interactive Design

Xiaotian Sun[1], Sitong Lu[1] ✉, and Jiaqi Fan[1, 2]

ABSTRACT

The demand for hand rehabilitation services is increasing currently, and there are many choices of hand rehabilitation products available on the market. Here, we report a flexible curvature sensor-based data glove, equipped with a built-in light trigger system, which is expected to provide active signal feedback for better human machine interface experience. By analyzing user needs and leveraging advancements in human-computer interaction, this new design not only facilitates physical recovery but also fosters a sense of ownership and motivation among patients. The incorporation of real-time feedback mechanisms further amplifies the efficacy of the rehabilitation process, propelling patients toward greater independence and self-assurance. Specially from an emotional point of view, the elements, such as functionality, design, color, material, and human-computer interaction, based on user needs, would be analyzed to summarize some core requirements. Then the performance of hand movements is integrated into the rehabilitation process through visual feedback to address the problem of monotony during training. This design can leverage the feedback mechanism between visual cues and hand movements, enhancing the sensory interaction experience between individuals and the product. Finally, it is proved by experiment this proposed design is very potential to help improve patients' motivation and self-efficacy in training, thereby enhancing the effectiveness of rehabilitation. By combining these elements, we believed that the design is expected to make up some emotional support for better human machine interface experience.

KEYWORDS

comfort; engagement and empowerment product design; finger angle sensing; visual feedback; effectiveness of rehabilitation; training initiative

Hand rehabilitation is an essential component within the broader realm of medical rehabilitation, Hand rehabilitation is not only a critical step in many brain rehabilitation processes, but also in cases where hand movement disorders or injuries are involved. As such, effective hand rehabilitation strategies are critical for restoring optimal hand function and improving overall well-being. Current treatments for hand movement disorders include range-of-motion exercises (exercises performed without weight bearing to improve joint mobility and relieve finger stiffness), Intensive training (weight bearing and use of rehabilitation equipment, bearing weight and using rehabilitation equipment to build muscle strength to support and protect the joints) and endurance training (to ensure the health of the cardiovascular system and reduce joint swelling)[1], The intervention methods can be roughly divided into two categories: central intervention and peripheral intervention. Traditional rehabilitation training cannot effectively meet the needs of hand function rehabilitation, so the application of emerging technology-assisted rehabilitation has attracted more and more attention.

Cao[2] developed an upper extremity exoskeleton rehabilitation system using motion bionics theory, incorporating sensors like angular displacement sensors, Flex Sensors, and accelerometers at joints to collect kinematic data of the healthy limb. This data is analyzed and processed using STM32, controlling the affected side's movement to mimic the healthy side's trajectory, facilitating rehabilitation. Li[3] developed a stroke rehabilitation device guiding the affected limb with data from the healthy limb's curvature, controlled by an inflatable airbag and a single-chip microcomputer to train hand movement. Liu[4] created a wearable device monitoring hemiplegic patients' hand movement, designing rehabilitation programs optimizing forced use and restriction-induced exercise therapy, setting a standard for future clinical trials. Wang[5] explored central nervous system rehabilitation mechanisms and limb motor function based on cross-transfer effects, proposing criteria for hand rehabilitation aids. These innovations collectively enhance stroke rehabilitation methodologies, from passive imitation to active training, aiming for comprehensive recovery and setting standards for future research and clinical applications.

We can also see the research results of other outstanding scholars on hand function rehabilitation gloves[6–9]. In these research, the biggest feature of this rehabilitation aid is the combination of virtual reality technology and hand function recovery, and the use of sensors for motion capture. In this way, the hand movements in the virtual reality scene can be controlled, and the patient training can be assisted in multiple dimensions.

Moital et al.[10] developed a portable myoelectric feedback system using healthy forearm signals to drive hand rehabilitation. Cempini et al.[11] designed an exoskeleton targeting spastic hand contractions, adjusting finger movements via motor control. Pichiorri et al.[12] created a virtual hand training system using EEG feedback to stimulate brain neurons. Pust et al.[13] designed a sensor array to locate stroke patients with motor dysfunction.

However, being in a virtual environment for a long time will easily cause visual fatigue. In addition, some rehabilitation medical

1 School of Mechanical and Materials Engineering, North China University of Technology, Beijing 100144, China
2 School of Human Comprehensive Sciences, University of Tsukuba, Tsukuba 305-8577, Japan
Address correspondence to Sitong Lu, lusitong018@163.com

institutions have started using hand function rehabilitation devices to replace physicians in providing rehabilitation treatment to patients. However, these types of rehabilitation devices mostly employ rigid structures[14–16], which have disadvantages such as poor flexibility, bulky structure, high cost, and the potential for causing secondary injuries to patients during use[17–19].

To address the aforementioned issues with rigid rehabilitation devices, researchers have introduced flexible materials into the field of hand function rehabilitation[20–26]. Studies have shown that hand function rehabilitation soft robots possess a certain degree of motion flexibility, allowing for better fit with the patient's hand. This meets the demands of patients for a soft, comfortable, home-based, portable, and cost-effective hand function rehabilitation robot. However, existing hand function rehabilitation products have issues with their mechanical configurations being unable to meet the flexible movement requirements of the hand's multiple degrees of freedom and lack of effective perception[27, 28].

To sum up, a user interview outline is developed from three perspectives: the severity of the patient's illness, the progress of rehabilitation training, and the user's opinions on data products. Offline user interviews with patients, their family members, and caregivers are then conducted, and the obtained information is summarized in Fig. 1.

In this paper, we develop a redesigned and innovative hand rehabilitation product aimed at helping patients improve the aforementioned concerns, enhancing visual feedback effects, increasing training motivation, and accelerating the rehabilitation process for stroke-related hand conditions.

1 Related Work

The core target user group for this product design is hand rehabilitation training patients. We collect their core needs and opinions on existing hand rehabilitation products through direct communication. At the same time, we conduct research on caregivers and family members to understand the patients' daily life conditions, the implementation of rehabilitation exercises, common rehabilitation methods during training, and psychological changes. Based on identified issues, we propose our own innovative ideas and corresponding improvements.

1.1 Analysis of product functional factors

According to the core needs of users, we found each requirement is mapped to the functional elements of the product. To summarize, the types of functions include wearable function, rehabilitation function and feedback function, as shown in Table 1.

Based on the above content, the product function is generally planned: this product will quantitatively detect the patient's hand joint mobility, and transmit the test results to the processor through electrical signals, and the results are given visual feedback on the screen, as shown in Fig. 2. In this paper, we define the patient's hand activity as two levels (bending angle > 45° and < 45°), and use different colors of Light-Emitting Diode (LED) lights to correspond them (Green: bending angle > 45°; Red: bending angle < 45°). When using this product, users could know the stage their hand activity level through the color change of the light on the screen, and directly feel the feedback on the degree of finger bending.

1.2 Analysis of product design factors

According to the core needs of users, we found each requi Appearance design is the key point in product design, which directly affects users' most intuitive and basic experience with products. When designing the appearance, we should not only

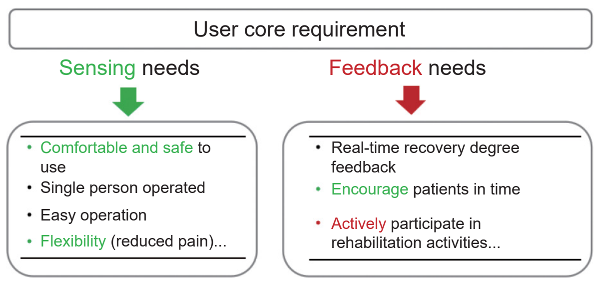

Fig. 1 Core product requirements based on literature and user research.

Table 1 Functional factors.

Wearable function	Rehabilitation function	Feedback function
Single person operated	Standardized rehabilitation training	Visual feedback
Portable	Easy operation	Real-time recovery degree feedback
Easy storage	Flexibility (reduced pain)	–

Fig. 2 The fabricated hand rehabilitation product integrated with curvature sensors and visual feedback element (LED).

provide functional requirements, but also consider the emotional experience of users when using it.

For rehabilitation products, the simple, soft and streamlined shape can provide patients with active participation and peace of mind, making the product more friendly, shortening the distance between the product and the patient, and reducing the patient's natural rejection of medical products.

Secondly, the hand rehabilitation product is directly worn on the hand and arm, and its appearance should match the patient's physiological structure and conform to the laws of ergonomics, at the same time avoid sharp corners or other protrusions, to ensure that patients can have a pleasant, safe and efficient rehabilitation training. The product use process should be simple, smooth and logical, avoid repeating wrong operations against the patient's self-confidence, and affect the enthusiasm of rehabilitation training.

In modern business competition, the appearance of a product plays a crucial role in attracting consumers. Industrial design Color, Material, Finishing (CMF) is an important design concept. In this regard, this article will also employ the design concept of CMF to create a product appearance that closely aligns with the aforementioned user needs.

A good CMF design can enhance the aesthetics of the product, prolong the service life of the product, and sublimate the value of the design. From the user's point of view, the emotional and user-centered design of the product will be displayed more clearly.

Color factor: Color elements have an important impact on the user's visual, mental and emotional experience and play a key role in the communication of information. Using the right color could help the product to perfect its function, improve the product's recognition and usability.

In the field of medical rehabilitation product design, products usually use black, white, gray, orange, green, blue and other colors, among which white, gray or black is the main color, and other colors are supplemented. Different colors will bring different psychological feelings and influences to users. For patients, the color design should try to choose low-brightness and low-saturation colors to bring patients a warm and natural feeling and soothe their emotions. Warm colors can also be used to bring optimism and positive feelings to patients. Or choose a neutral color that can produce a healthy, stable, and comfortable mood to reduce the patient's negative emotions.

Material factor: Material is the basic carrier for the product to realize the basic and even emotional function, among which color, texture, texture and other aspects are important considerations for material selection. In the design of hand rehabilitation products, the materials selection should follow the following points:

(1) Try to use materials with soft visual experience to give patients warm and calm feelings and improve the affinity of the product.

(2) Choose the materials that provide warm qualities, such as cloth, leather, plastic, or rubber, to enhance the comfort of the product when in contact with the skin.

(3) Choose a variety of materials to avoid the negative experience brought by only using a single material.

(4) Due to the weak hand strength of the patient, we need to choose drop-resistant, wear-resistant, high-toughness materials, to prolong the service life of the product.

Surface design: Plastic, silicone and other materials are usually used in the design of rehabilitation products. In order to ensure the safety of patients, it is recommended to use frosting and other processes on the surface to improve the friction, skin-friendly and anti-skid properties of the product surface. This design strategy can not only improve the product experience, but also increase the layering and visual effects of the product, thereby improving the overall product quality.

Interaction factor:

(1) Interactive action setting.

This product is designed for rehabilitation training of hand grasping function and flexion and extension function.

According to the core user needs, the training movements need to be simple and effective, and can be done alone at home.

Therefore, this project sets the simple clenching, bending and stretching movements of simulating the hand grasping objects as the designated rehabilitation training movements.

Through repeated fisting/grasping exercises, patients can increase hand muscle strength, improve finger joint mobility, and improve overall hand coordination.

(2) Other interactive factors.

The process of hand rehabilitation is generally very long. If the training method is boring and lacks feedback, it may lead to low motivation of patients in rehabilitation.

Therefore, the use of visual feedback provides patients with more psychological and emotional support, allowing patients to intuitively understand their level of hand mobility when using the product, and to better feel the process of their own rehabilitation progress. In the subsequent design phase, the simple LED light feedback will be upgraded to a more attention-grabbing and emotionally positive experiential design, such as animations on a screen.

2 Design Prototype

Following comprehensive user research, design factor analysis, and functional prototype verification evaluation, this chapter will embark on the practical design implementation of hand rehabilitation products.

Concept development: Post finalizing the product prototype design, a structured brainstorming session will be conducted to foster divergent thinking and explore various design aspects encompassing style, modeling features, function realization, structural components, and other essential elements related to hand rehabilitation products.

The product's prototype design is segmented into two parts, specifically the hand device and the wrist device, with a detailed sketch scheme depicted in Fig. 3. This design alignment is intricately linked to the product's functional requirements and prototype structure.

Upon completion of the prototype design phase, a thorough discussion will ensue to select a suitable sketch scheme, considering factors like product function, shape, CMF, interaction, and other pertinent aspects. Subsequently, a detailed design description of the chosen sketch scheme will be provided.

The hand device predominantly comprises plastic components supplemented with fabric, housing a storage compartment intricately connected to four bending sensors enabling unrestricted movement aligned with the joints.

Likewise, the wrist section, composed of plastic and fabric elements, integrates electronic components such as development boards and LEDs. It is equipped with wire connection openings and power ports for enhanced functionality.

Moreover, the sensors transmit signals to the development board, enabling control over feedback lights to generate multi-color changes. Patients can monitor the recovery progress of specific fingers based on the feedback light signals.

Structural refinement: The design scheme will be further refined based on the initial sketch, focusing on enhancing

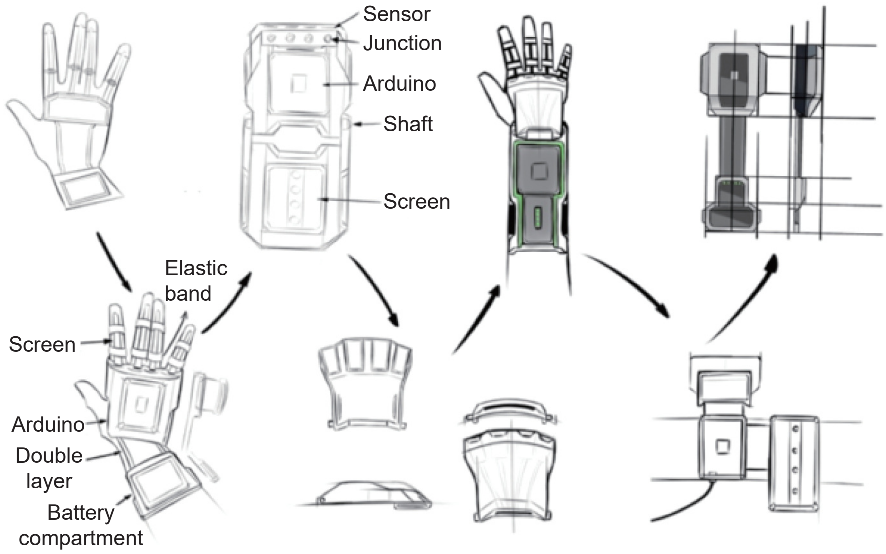

Fig. 3 Prototype sketch.

functional integrity, structural rationality, and detailed in-depth design considerations, as illustrated in Fig. 4.

3D modeling: Following the refinement of the sketch, SolidWorks software will be utilized to construct a comprehensive 3D model, showcasing each part intricately, as depicted in Fig. 5.

Visualization: Post finalizing the product design plan, the final model will be imported into Keyshot for rendering, where design factors like materials, colors, and craftsmanship will be fine-tuned to produce realistic renderings, as presented in Fig. 6.

3 Removable Embedded Sensing Module

The user interface is designed to be user-friendly, featuring clear and concise information display that is easily understandable by patients of varying ages and technological proficiency levels. Visual cues, such as color changes in the LED lights, are accompanied by accompanying audio cues for a multi-sensory feedback experience, catering to different learning preferences and accessibility needs.

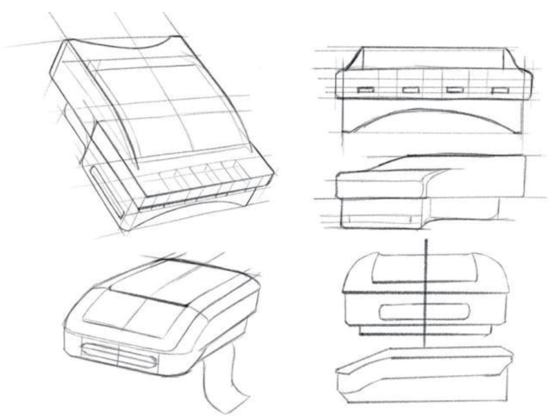

Fig. 4 Product details sketch.

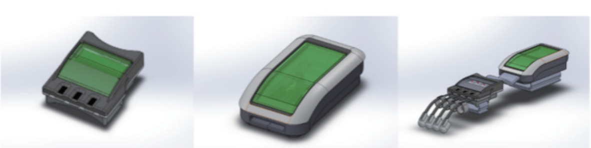

Fig. 5 Product details preview.

In the future, the product incorporates gamification elements to make the rehabilitation process more engaging and motivating for patients. By setting achievable goals and milestones that are represented through visual feedback on the device, patients are encouraged to actively participate in their rehabilitation journey. This gamified approach not only increases patient motivation but also fosters a sense of accomplishment and progress tracking throughout the rehabilitation process.

We will also design richer animation effects in interactive design for customization and personalization options, enabling patients to set their preferences for feedback intensity, color schemes, and goal settings. This level of personalization empowers patients to take control of their rehabilitation experience and tailor it to their individual needs and preferences, thereby promoting a sense of ownership and autonomy in their recovery journey.

Overall, through the integration of interactive design principles, gamification elements, and user customization features, the rehabilitation product aims to revolutionize the patient experience by not only facilitating physical recovery but also nurturing emotional well-being and motivation throughout the rehabilitation process. This holistic approach to design not only enhances the effectiveness of rehabilitation but also creates a more positive and empowering experience for patients on their road to recovery.

3.1 Finger curvature measurement

Fig. 6 Product rendering.

The assigned rehabilitation training exercise in this paper involves simulating the grasping and flexion/extension movements of the hand. Therefore, it is necessary to select a bending sensor to quantitatively measure the degree of hand flexion and provide data feedback. Here the chosen model is the Flex2.2 uniaxial bending sensor, as shown in Fig. 7, with its technical specifications listed in Table 2. Flexible bending sensors in this product serve as devices that provide feedback on the degree of finger bending. Since finger bending involves shape changes, rigid sensors are not suitable for this scenario. The bending sensor can be affixed and fixed on the back of one finger, and the output resistance value of the sensor will increase when the finger is flexed and extended, as shown in the right in Fig. 7.

3.2 Signal acquisition system

In order to provide real-time feedback for the rehabilitation effectiveness in this paper, a variable color LED light array is used to convert the data signal into different colors of light, conveying feedback information through the change in light color. The chosen model is the ROBOMAKE bi-color LED common cathode sensor module, as shown in Fig. 8. The bi-color LED (bi-color light-emitting diode) refers to a module that can display two colors, typically red and green, and can have three different states: off, red, and green. Of course, depending on the combination of colors, it can be categorized as red-blue bi-color, yellow-blue bi-color, red-green bi-color, and so on. In this paper, however, we only use red and green for application.

Using visual feedback provides patients with added psychological and emotional support, enabling them to have a visual understanding of their hand's activity level while using the product. It also enhances their perception of the progress made during the rehabilitation process.

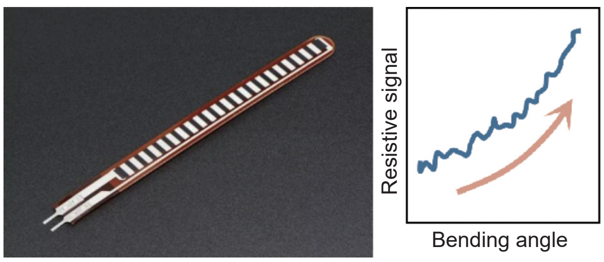

Fig. 7 Flex2.2 sensor and its sensing signal changing trend with the increase of finger bending.

Table 2 Typical properties of Flex2.2 sensor.

Property	Typical value
Initial resistance	25 kΩ
Resistance change	10–125 kΩ
Flexible life	>1 million times
Working temperature	−35℃–+80℃
Size	77 mm × 6.35 mm (length × width)

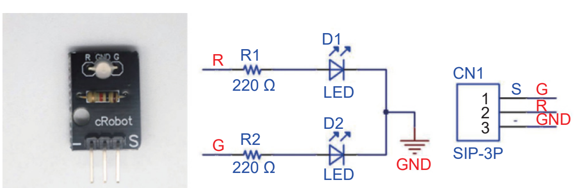

Fig. 8 (a) Image of bi-color LED and (b) circuit schematic diagram.

3.3 Interactive function implementation

The visual feedback functional prototype is completed based on the Arduino Leonardo development board to construct the hardware system, and the hardware completion effect can be shown in Fig. 9.

This product quantitatively measures the patient's hand joint mobility and transmits the test results to a processor through electrical signals. The processor controls LED lights on the product to provide visual feedback in the form of bright lights corresponding to the results. The patient's hand mobility level is defined in different stages, and each stage is associated with a different color of LED light. When using this product, users can determine their hand mobility level based on the color changes of the lights, directly experiencing the recovery effects of rehabilitation.

The final functional prototype of the product is built using the Arduino Leonardo development board. The schematic diagram of the prototype is shown in the figure. The motion feedback of the functional prototype is achieved by providing corresponding LED color changes based on the values of the flex sensors during stroke patients' rehabilitation training. During rehabilitation training, the flex sensors continuously sense the bending angle of the patient's finger joints. The resistance of the sensors changes accordingly, and the Arduino UNO development board converts it into a voltage signal representing the corresponding intensity of change. This signal drives the LED lights to change colors accordingly. When the bending angle of the patient's hand joints reaches the normal range during training, the LED lights change color, allowing the patient to understand their hand mobility level. The functional prototype achieves hardware control through Arduino IDE, as shown in the figure.

I/O ports P1–P4 of Microcontroller (Arduino Leonardo) are linked with every bending sensor put on every finger. Assistant I/O ports are connected to the data acquisition card (PCI-1 710, Taiwan) in order to receive control commands. Port VIN (unregulated power in) and port VSS (system ground) is

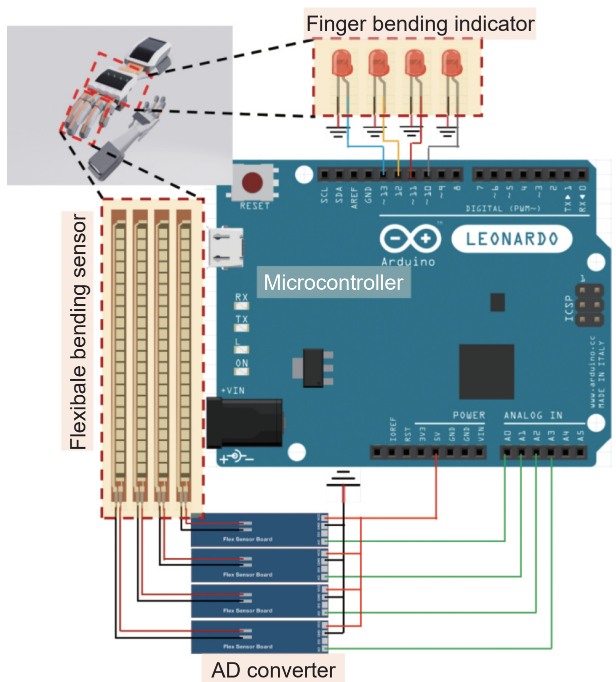

Fig. 9 Experimental setup of the four flexible curvature sensor imbedded the hand rehabilitation product.

connected to a constant voltage source.

The motion performance feedback of the functional prototype is provided to patients during their rehabilitation training process based on the changes in values from the flex sensor, which corresponds to LED color variations, as shown in Fig. 10. During the rehabilitation training, the flex sensor continuously detects the bending angle of the patient's finger joints. As the sensor's resistance changes accordingly, the Arduino development board converts it into a corresponding voltage signal, which results in color variations in the LED array. When the patient's hand joint reaches the normal bending angle during training, the color of the LED array changes, allowing the patient to understand their hand' s level of motor ability. The functional prototype utilizes Arduino IDE as a compilation environment for software development.

4 Performance Verification

To further validate the effectiveness of the interactive design innovations in the hand rehabilitation product, a pilot program was conducted with five individuals who were experiencing hand-related issues and required rehabilitation. These participants were selected to engage with the product, experience its features firsthand, and provide feedback through interviews to assess the impact of the design on their rehabilitation journey.

The participants were guided through using the rehabilitation product, interacting with the feedback mechanisms, engaging with the gamification elements, and customizing settings according to their preferences. Throughout the pilot program, participants were encouraged to actively participate in their rehabilitation activities and track their progress using the product's features.

After a period of engaging with the product, interviews were conducted with each participant to gather qualitative feedback on their experience. The interviews aimed to uncover insights into the participants' perspectives on the usability, engagement, motivation, and overall impact of the interactive design features on their rehabilitation process.

The participants reported overwhelmingly positive feedback regarding their experience with the hand rehabilitation product. They highlighted the following key benefits:

Increased motivation: Participants expressed that the gamified approach and visual feedback motivated them to engage consistently in their rehabilitation exercises and track their progress.

Enhanced user engagement: The intuitive user interface design and interactive features captured the participants' interest and encouraged active participation in their rehabilitation journey.

Personalization and control: Customization options allowed participants to tailor their experience to their preferences, contributing to a sense of ownership and autonomy in their recovery process.

Emotional well-being: The positive reinforcement provided by the product's feedback mechanisms fostered a sense of accomplishment and boosted participants' emotional well-being throughout their rehabilitation.

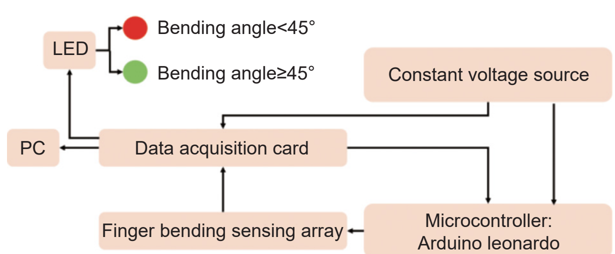

Fig. 10 Workflow chart of overall sensing system.

In addition to the positive feedback received from the participants in the pilot program, valuable insights were also gathered regarding potential areas for improvement in the hand rehabilitation product. Based on the participants' feedback, the following suggestions for enhancements were identified:

Enhanced data tracking: Participants expressed interest in more detailed data tracking and progress monitoring features. Improving the data visualization and providing insights into their performance over time could further motivate users to stay on track with their rehabilitation goals.

Greater customization options: While the customization features were appreciated, participants suggested expanding the range of customization options available. Providing additional choices for feedback settings, game difficulty levels, and personalization features could cater to a broader range of user preferences and needs.

Interactive challenges and rewards: Participants recommended incorporating more interactive challenges and rewards to add variety and entertainment value to the rehabilitation activities. Introducing different game modes, achievements, and incentives could make the rehabilitation process more engaging and enjoyable.

Integration with telehealth services: Some participants expressed interest in the possibility of integrating the product with telehealth services to receive remote guidance and feedback from healthcare professionals. Offering tele-rehabilitation options could enhance the support and guidance available to users during their recovery journey.

Accessibility features: Participants highlighted the importance of ensuring the product is accessible to users with diverse needs, including those with mobility or sensory challenges. Incorporating accessibility features such as voice commands, haptic feedback, or alternative control methods could make the product more inclusive and user-friendly.

Overall, the feedback from the five participants in the pilot program underscored the significant positive impact of the interactive design innovations in the hand rehabilitation product. As shown in Fig. 11, their experiences highlighted the successful integration of sensor technology, user interface design, gamification elements, and customization features in enhancing the rehabilitation journey and promoting user engagement, motivation, and empowerment. The findings from these interviews reinforced the value of the interactive design approach in revolutionizing the patient experience and fostering positive outcomes in hand rehabilitation. By incorporating these suggestions for improvement, the hand rehabilitation product can evolve to better meet the varying needs and preferences of users, enhance user engagement and motivation, and further optimize the rehabilitation experience. Continuous feedback and iterative design refinements based on user insights will be essential in advancing the product and ensuring its ongoing relevance and effectiveness in supporting individuals on their journey to hand recovery.

5 Conclusion

The field of hand rehabilitation is vital for individuals facing hand function impairments, as it greatly impacts their ability to perform daily activities and maintain independence. Traditional rehabilitation methods often have limitations in meeting the diverse needs of patients, leading to the exploration of emerging technologies and innovative designs in rehabilitation products.

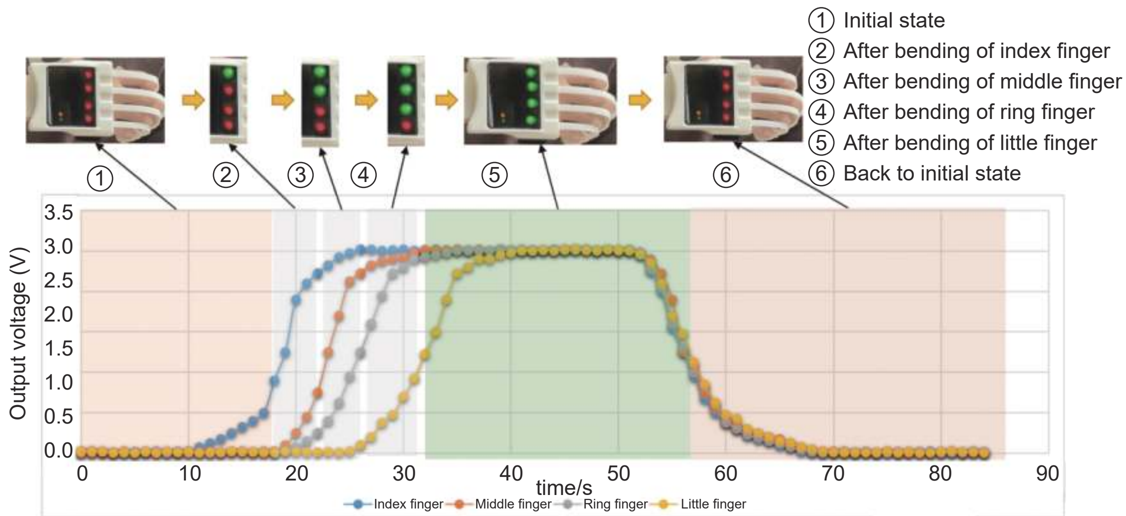

Fig. 11 Output voltage change profile of the four flexible curvature sensors during the different actions.

Existing technologies encompass a wide range of solutions, from upper extremity exoskeletons to myoelectric feedback systems and virtual reality-based rehabilitation aids. However, many of these devices suffer from drawbacks such as rigidity, lack of flexibility, and passive training methods, which can hinder patient progress.

To address these issues, this paper introduces a novel approach: hand rehabilitation training installation through interactive design. This innovative design integrates curvature sensors to quantify hand joint mobility and provides real-time visual feedback through LED lights. By using different colors to represent various levels of hand activity, patients can easily track their progress during rehabilitation sessions. This real-time feedback mechanism enhances patient engagement and motivation, fostering a sense of ownership and empowerment in their rehabilitation journey.

The design factors, including appearance, color, material, and human-computer interaction, are carefully considered to meet user needs and provide a comfortable and emotionally supportive experience. The product's soft and streamlined design aims to reduce patient rejection of medical devices and ensure ergonomic fit, thereby enhancing user acceptance and compliance.

Furthermore, the paper outlines the comprehensive design process, from initial conceptualization to prototype development. Sketches, 3D models, and functional prototypes demonstrate the evolution of the product design, ensuring functionality, safety, and user-friendliness.

Performance verification tests validate the effectiveness of the proposed design, showing real-time color changes in response to finger movements. This feedback mechanism enhances the rehabilitation process, promoting patient independence and confidence. The real-time feedback mechanism is developed to integrate into the designed data glove while taking tracking the participants' hand moving stages for instance. Light color (red-yellow-green) could change according to different sensing signal amplitudes. It is expected to make up some emotional support for better human machine interface experience.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (No. 52205001).

Article History

Received: 2 December 2023; Revised: 8 July 2024; Accepted: 23 July 2024

References

[1] I. V. A. N. Grubišić, S. K. Hana, and G. Simeon, Novel approaches in hand rehabilitation, *Period. Biologorum*, vol. 117, no. 1, pp. 139–145, 2015.

[2] H. S. Cao, Design and study of a wearable upper limb exoskeleton, PhD dissertation, Shanghai Jiao Tong University, China, 2017.

[3] M. Y. Li, Research on stroke rehabilitation equipment based on healthy limb, master's dissertation, Yanshan University, China, 2017.

[4] X. C. Liu, Design research of product and treatment design to simulate stroke hemiplegic patients to use their more-involved limbs during daily lives, master's dissertation, Zhejiang University, China, 2018.

[5] Z. L. Wang, Design of hand rehabilitation aids for stroke patients based on cross-education effect, master's dissertation, Shandong University, China, 2021.

[6] L. Zhou, Intelligent music rehabilitation hand based on voice recognition, *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 612, no. 4, p. 042080, 2019.

[7] S. H. Yang, C. L. Koh, C. H. Hsu, P. C. Chen, J. W. Chen, Y. H. Lan, Y. Yang, Y. D. Lin, C. H. Wu, H. K. Liu, et al., An instrumented glove-controlled portable hand-exoskeleton for bilateral hand rehabilitation, *Biosensors*, vol. 11, no. 12, pp. 495, 2021.

[8] The James Dyson Foundation, HOPES, https://www.jamesdysonaward.org/zh-CN/2021/project/hopes/, 2023.

[9] S. Ueki, H. Kawasaki, S. Ito, Y. Nishimoto, M. Abe, T. Aoki, Y. Ishigure, T. Ojika, and T. Mouri, Development of a hand-assist robot with multi-degrees-of-freedom for rehabilitation therapy, *IEEE/ASME Trans. Mechatron.*, vol. 17, no. 1, pp. 136–146, 2012.

[10] A. R. Moital, S. Dogramadzi, and H. A. Ferreira, Development of an EMG controlled hand exoskeleton for post-stroke rehabilitation, in *Proc. 3rd 2015 Workshop on ICTs for improving Patients Rehabilitation Research Techniques*, Lisbon, Portugal, 2015, pp. 66–722.

[11] M. Cempini, S. M. M. De Rossi, T. Lenzi, M. Cortese, F. Giovacchini, N. Vitiello, and M. C. Carrozza, Kinematics and design of a portable and wearable exoskeleton for hand rehabilitation, in *Proc. IEEE 13th Int. Conf. Rehabilitation Robotics (ICORR)*, Seattle, WA, USA, 2013, pp. 1–6.

[12] F. Pichiorri, G. Morone, M. Petti, J. Toppi, I. Pisotta, M. Molinari, S. Paolucci, M. Inghilleri, L. Astolfi, F. Cincotti, et al., Brain–computer interface boosts motor imagery practice during stroke recovery, *Ann. Neurol.*, vol. 77, no. 5, pp. 851–865, 2015.

[13] M. Pust, E. Ivanova, H. Schmidt, and J. Krüger, Design of a pressure sensitive matrix for analyzing direct haptic patient-therapist interaction in motor rehabilitation after stroke, *Curr. Dir. Biomed. Eng.*, vol. 3, no. 1, pp. 57–61, 2017.

[14] P. Heo, G. M. Gu, S. J. Lee, K. Rhee, and J. Kim, Current hand exoskeleton technologies for rehabilitation and assistive engineering, *Int. J. Precis. Eng. Manuf.*, vol. 13, no. 5, pp. 807–824, 2012.

[15] Z. Yue, X. Zhang, and J. Wang, Hand rehabilitation robotics on poststroke motor recovery, *Behav. Neurol.*, vol. 2017, p. 3908135, 2017.

[16] M. V. Arteaga, J. C. Castiblanco, I. F. Mondragon, J. D. Colorado, and C. Alvarado-Rojas, EMG-driven hand model based on the classification of individual finger movements, *Biomed. Signal Process. Contr.*, vol. 58, pp. 101834, 2020.

[17] Y. Liu, X. Li, A. Zhu, Z. Zheng, and H. Zhu, Design and evaluation of a surface electromyography-controlled lightweight upper arm exoskeleton rehabilitation robot, *Int. J. Adv. Rob. Syst.*, vol. 18, no. 3, p. 172988142110034, 2021.

[18] T. du Plessis, K. Djouani, and C. Oosthuizen, A review of active hand exoskeletons for rehabilitation and assistance, *Robotics*, vol. 10, no. 1, pp. 40, 2021.

[19] P. Tran, S. Jeong, K. Herrin, and J. Desai, Review: Hand exoskeleton systems, clinical rehabilitation practices, and future prospects, *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 3, pp. 606–622, 2021.

[20] C. Laschi, B. Mazzolai, and M. Cianchetti, Soft robotics: Technologies and systems pushing the boundaries of robot abilities, *Sci. Robot.*, vol. 1, no. 1, p. eaah3690, 2016.

[21] T. Shahid, D. Gouwanda, S. G. Nurzaman, and A. A. Gopalai, Moving toward soft robotics: A decade review of the design of hand exoskeletons, *Biomimetics*, vol. 3, no. 3, p. 17, 2018.

[22] P. W. Ferguson, Y. Shen, and J. Rosen, Hand exoskeleton systems—Overview, in *Wearable Robotics*, J. Rosen and P. W. Ferguson Eds. Amsterdam, The Netherlands: Elsevier, 2020, pp. 149–175.

[23] C. G. Rose and M. K. O'Malley, Hybrid rigid-soft hand exoskeleton to assist functional dexterity, *IEEE Robot. Autom. Lett.*, vol. 4, no. 1, pp. 73–80, 2019.

[24] M. Sarac, M. Solazzi, and A. Frisoli, Design requirements of generic hand exoskeletons and survey of hand exoskeletons for rehabilitation, assistive, or haptic use, *IEEE Trans. Haptics*, vol. 12, no. 4, pp. 400–413, 2019.

[25] M. H. Abdelhafiz, L. N. S. Andreasen Struijk, S. Dosen, and E. G. Spaich, Biomimetic tendon-based mechanism for finger flexion and extension in a soft hand exoskeleton: Design and experimental assessment, *Sensors*, vol. 23, no. 4, p. 2272, 2023.

[26] T. Bagneschi, D. Chiaradia, G. Righi, G. Del Popolo, A. Frisoli, and D. Leonardis, A soft hand exoskeleton with a novel tendon layout to improve stable wearing in grasping assistance, *IEEE Trans. Haptics*, vol. 16, no. 2, pp. 311–321, 2023.

[27] R. C. Silva, B. G. Lourenço, P. H. F. Ulhoa, E. A. F. Dias, F. L. da Cunha, C. P. Tonetto, L. G. Villani, C. B. S. Vimieiro, G. A. Lepski, M. Monjardim, et al., Biomimetic design of a tendon-driven myoelectric soft hand exoskeleton for upper-limb rehabilitation, *Biomimetics*, vol. 8, no. 3, p. 317, 2023.

[28] T. Bützer, O. Lambercy, J. Arata, and R. Gassert, Fully wearable actuated soft exoskeleton for grasping assistance in everyday activities, *Soft Robot.*, vol. 8, no. 2, pp. 128–143, 2021.