

Design of Home-based Rehabilitation Robot Using Joint-automated-combat-knowledge Virtual Simulation for Patients with Upper Limb Hemiplegia

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We designed a training robot for home-based limb rehabilitation by integrating joint-automated-combat-knowledge (JACK) virtual simulation. The robot addresses the need for motor function rehabilitation of hemiplegic patients at home. To design the robot, we conducted a literature review on upper limb hemiplegia and conventional rehabilitation robots, and analyzed the training method for patients with upper limb hemiplegia using the rapid upper limb assessment method and JACK software. As a result, posture risks associated with various movements without robotic assistance were assessed and identified. The needs of the patients were also identified through interviews to refine the design of the upper limb rehabilitation robot. The applicability of the robot was evaluated by JACK simulation analysis, and the results demonstrated that the robot significantly enhanced patient comfort and safety in rehabilitation training.

1. Introduction

The number of hemiplegic patients with various chronic diseases has been increasing globally. Approximately 80% of the patients experience impaired motor function in the affected limb, whereas 30–36% are suffering from upper limb dysfunction 6 months post-onset, leading to unsatisfactory recovery outcomes and diminished daily abilities and quality of life. Rehabilitation training enables around 90% of hemiplegic patients to regain self-care abilities, whereas the rate is as low as 5% for those without training. However, many hemiplegic patients discontinue rehabilitation after being discharged from hospitals. In addition, 75% of patients employ incorrect training methods, and 64% suffer injuries owing to excessive training.⁽¹⁾ The discontinuation of the rehabilitation training by hemiplegic patients is due to a lack of professional guidance, assistive devices for home-based rehabilitation, and a scientific rehabilitation training system and the guidance for its use.

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Therefore, we evaluated postural risks during upper limb rehabilitation training and related user needs through interviews. Human-machine dimensions were determined in simulations using joint-automated-combat-knowledge (JACK) software to design a training robot for home-based limb rehabilitation. Sensors are important in JACK simulation to enhance the accuracy of ergonomic analysis.

JACK is often integrated with external motion capture sensors in inertial-magnetic systems (wearable sensors) and optical/vision-based systems. Inertial-magnetic systems employ small sensors worn on the body to track movement and orientation and collect field-based data. In the inertial-magnetic system, inertial measurement units (IMUs), accelerometers, gyroscopes, and magnetometers are included. The data from these sensors is fused using algorithms such as the Kalman filter to calculate the precise 3D orientation and motion of body segments. This motion data is imported into the JACK software, which drives the digital human model (DHM) to mimic the real person's actions. On the basis of the data collected by the sensors, JACK simulation is conducted to identify ergonomic factors such as lumbar forces and joint angles. Movements in various tasks, such as lifting or carrying, are also monitored using sensors.⁽²⁾

Optical/vision-based systems track physical markers or body features using data obtained from infrared (IR) cameras and reflective markers. Small, reflective markers are placed on specific anatomical landmarks of the human body. The IR cameras track the 3D position of these markers, and the captured motion data is used to drive the joint angles of the DHM in JACK, often in real time in virtual reality (VR). In a markerless vision system, depth cameras or stereo-/multiple cameras are integrated with JACK to capture depth and color information to estimate the human body's posture and joint locations. The output is used to scale DHM in JACK to match the scanned individual's body size and shape, or to capture and stream movement data for real-time simulation and ergonomic analysis.⁽³⁾

On the basis of available sensor data, we designed a robot using the JACK simulation method for the home-based rehabilitation of patients with upper limb hemiplegia. The design serves as a reference for developing various robots for rehabilitation purposes.

2. Upper Limb Rehabilitation Robot

Rehabilitation robots belong to a key category of medical service robotics. Medical device companies establish industry standards to develop technological and industrial ecosystems and continuously advance intelligent rehabilitation services by accommodating various rehabilitation purposes and stages.⁽⁴⁾ Primarily designed to address motor function impairments, rehabilitation robots are used for secondary applications such as sensory and cognitive function rehabilitation, assisting patients in regaining movement abilities. Upper limb hemiplegia is one of the most common motor function impairments, particularly among hemiplegic patients with stroke, as many of them lose the ability to perform daily tasks independently and require extensive caregiving. Through assisted training with rehabilitation robots, rehabilitation effectiveness can be enhanced, helping patients regain a certain level of upper limb mobility and achieve a certain degree of self-care. This approach not only lowers the cost of care during rehabilitation but also enhances training efficiency.

Existing upper limb rehabilitation robots are classified into the following categories based on their therapeutic approach. The robots guide the patient's upper limb movements along a predefined trajectory.

2.1 Continuous passive motion (CPM) therapy

The rehabilitation robot eliminates the need for any voluntary effort from the patient. The rehabilitation robots are mainly employed for stroke patients who have completely lost sensation and motor control in the affected upper limb. Rehabilitation therapists determine the movement trajectories of rehabilitation robots on the basis of the severity of each patient's upper limb impairment.

2.2 Active-assisted therapy

In this therapy, the rehabilitation robot is mainly used for patients who retain residual movement ability but lack the control to complete movements effectively. This therapy is commonly applied in shoulder and elbow rehabilitation.

2.3 Active-resistive therapy

In this therapy, the rehabilitation robot is particularly beneficial for stroke patients who still retain limited mobility in their upper limbs but lack the control for purposeful movement. In the rehabilitation process, patients can attempt to move their impaired upper limbs voluntarily with the help of the robot. The rehabilitation robot captures the patient's motion data using electromyography and monitors the corresponding movement trajectory. If patients are unable to maintain the movement as intended, the rehabilitation robot applies external force to guide the impaired limb back to the correct trajectory and ensure that the rehabilitation exercises are carried out correctly and effectively.

2.4 Bilateral therapy

This therapy requires the patient to have one fully functional upper limb. By moving the unaffected limb, the rehabilitation robot replicates the motion trajectory onto the impaired limb, enabling controlled and synchronized mirror movements. Throughout this process, the patient maintains full control over the movement of the unaffected upper limb, while the rehabilitation robot assists patients with the impaired limb in performing the mirrored movements and completing the rehabilitation exercises.⁽⁵⁾

The comparison of the different categories of upper limb rehabilitation robots in terms of patient suitability, operational principles, and targeted training areas is summarized in Table 1. Upper limb rehabilitation robots are also classified on the basis of their structural design and operational principles: end-effector robots and exoskeleton robots. These two types of upper limb rehabilitation robots are presented in Fig. 1.

Table 1
Feature comparison of different categories of upper limb rehabilitation robots in different therapies.

Therapy Modality	Primary patient group	Basic working principle	Therapeutic effect characteristics
CPM therapy	Hemiplegic patients with insensate upper limbs	Guide passive flexion and stretch of the upper limb	Focus on upper limb training
Active-assisted therapy	Patients with partial mobility	Provide force assistance to facilitate patient movement	Target shoulder and elbow training
Active-resistive therapy	Patients with partial mobility	Provide force assistance to interfere with patient movement	Focus on arm training
Bilateral therapy	Patients with one fully functional upper limb	Mirrors movement trajectories of the unimpaired upper limb	Focus on upper limb training

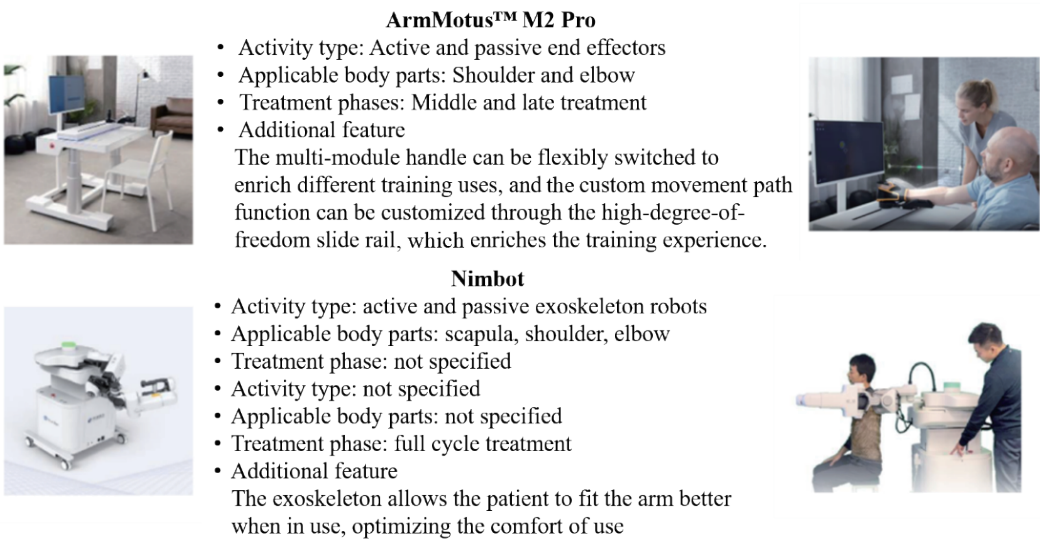


Fig. 1. (Color online) End-effector robot (ArmModus) and exoskeleton robot (Nimbot) for upper limb rehabilitation.

2.4.1 End-effector robot

An end-effector robot features a movable handle that patients grip, enabling patients to move their upper limbs following a preprogrammed rehabilitation trajectory of the rehabilitation robot. The end-effector of the robot adopts force sensors and position/motion sensors for measuring the patient's interaction with the robot, which is critical for rehabilitation. Force sensors are mounted at the robot's wrist joint (between the final link of the arm and the handle) or directly within the handle mechanism. Position/motion sensors are used to track the handle's movement, which is related to the patient's limb position. End-effector robots are generally used in the mid-to-late stages of rehabilitation, providing relatively high levels of movement freedom.

2.4.2 Exoskeleton robot

Exoskeleton robots are distinguished by mechanical arms equipped with splints or bionic structures. Patients secure their upper limbs to the robotic arm, which guides the movement based on predetermined joint torques and motion trajectories. Exoskeleton robots are designed for full-cycle rehabilitation, offering a more anatomically aligned fit throughout the entire process.⁽⁶⁾

3. Applicability of Robot in Home-based Rehabilitation

Home-based rehabilitation is important in rehabilitation healthcare. However, because of multiple unfavorable factors, including late development, immature environments, and complex standardization processes, rehabilitation robots have not been used widely. In contrast, the number of hemiplegic patients is increasing, and many of them opt for home-based rehabilitation therapy and training to shorten lengthy rehabilitation cycles, reduce high hospitalization costs, and address an imbalance in supply and demand.

Home-based rehabilitation training does not apply to all hemiplegic patients. Upper limb hemiplegia is classified into six levels on the basis of the degree of muscle strength impairment (Fig. 2). Patients with muscle strength levels 3 and 4 retain limited mobility of their limbs but have lower performance requirements for rehabilitation robots than those at higher levels. This necessitates home-use solutions. Patients at these levels of impairment require complete and appropriate rehabilitation training at home.⁽⁷⁾

The scapula, shoulder, elbow, wrist, and hand can be rehabilitated for patients with upper limb hemiplegia to improve the motor ability of the wrist and hand and the functions of the shoulder and elbow.⁽⁸⁾ For home-based rehabilitation and training, the upper limb rehabilitation robot needs to adopt various designs for the targeted rehabilitation parts.⁽⁹⁾ End-effector robots can address the rehabilitation of multiple parts owing to their structural versatility. However, few end-effector robots are available for home rehabilitation, although most patients need to perform exercises with assistive devices under the supervision of caregivers at home. Therefore, we

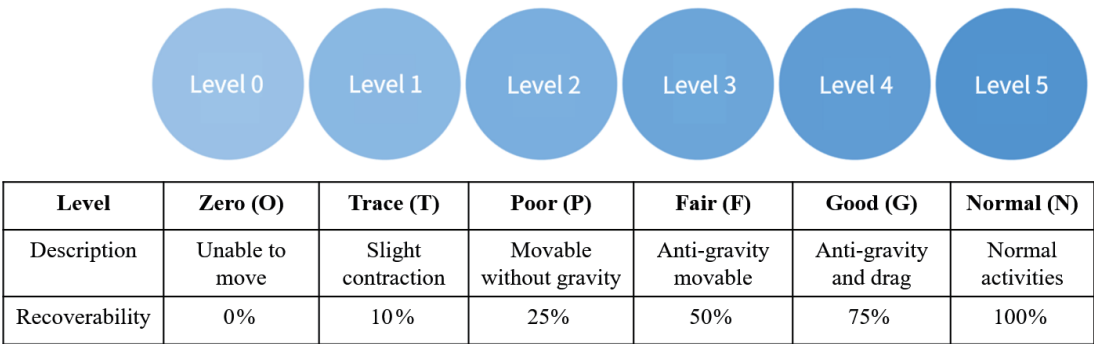


Fig. 2. (Color online) Six levels of muscle strength impairment in patients with upper limb hemiplegia (Based on the classification of muscle strength, user groups were selected).

designed an end-effector robot for upper limb rehabilitation at home for patients with muscle strength levels 3 to 4 to independently engage in rehabilitation training.

4. Simulation for Upper Limb Assessment

4.1 Rapid upper limb assessment (RULA) and JACK simulation

For musculoskeletal disorder (MSD) and risk assessment, RULA, loading on the upper body assessment (LUBA), and the Ovako working posture analysis system (OWAS) are usually used.⁽¹⁰⁾ Among them, RULA is the most widely used to assess the feasibility of a motion capture system combined with VR headsets to simulate occupational tasks. RULA is also used to evaluate the risks associated with kangaroo care postures in hospitals and design an ergonomic chair to reduce caregiver injury risks.⁽¹¹⁾ RULA has been proven to be effective in the quick assessment of risks in the upper limb. RULA is applied to the two groups of human body parts: Group A (upper arm, forearm, and wrist) and Group B (neck, trunk, and legs). On the basis of posture scores for Groups A and B, the muscle use and applied force are weighted to obtain scores C and D. These scores are then combined to calculate the final evaluation score, as shown in Fig. 3.

In the JACK simulation, RULA posture scores for Group A and Group B are given on the basis of the data from kinematic sensors. IMUs combined with accelerometers, gyroscopes, and magnetometers are used to track joint angles. The data from these sensors drives the DHM's posture in the simulation, allowing the software's RULA module to calculate the accurate posture scores. To measure the necessary force and load, load cells or digital force gauges are used to measure the precise magnitude of the external force being exerted or the load carried during the task. This measured force is input into the DHM simulation to accurately calculate the required RULA weighting factor. The weighting for muscle use is supplemented by using physiological sensors. Surface electromyography (sEMG) sensors are applied to the skin over relevant muscles to measure muscle activity and fatigue, providing robust, real-time data to justify the score applied for muscle use in the RULA analysis. Since RULA is inherently a scoring methodology, its contemporary application in advanced simulation tools leverages

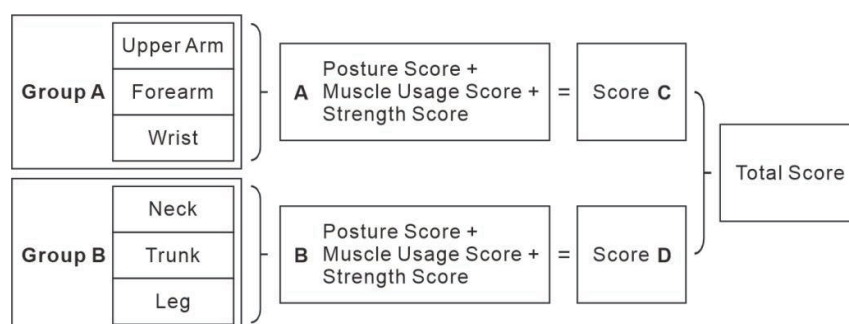


Fig. 3. Risk assessment and calculation method of RULA.

diverse sensor data to transform subjective or observational assessments into precise, quantitative ergonomic evaluations. The RULA score and its corresponding fatigue levels and classification meanings are presented in Table 2.⁽¹²⁾

4.2 Virtual simulation

We selected the Chinese body dimension database to create a digital model of the patient's body in the JACK software. The model of the rehabilitation robot was imported, and a simulation scenario was created. Since the rehabilitation robot must meet the needs of patients, the Chinese adult body dimensions of the 95th percentile male (P95) and the 5th percentile female (P5) were chosen as the size range limits. The impact of the patient's posture on the upper limb musculoskeletal system in assisted task simulation was evaluated using RULA and the JACK software. The virtual character models used in the simulation are shown in Fig. 4.

4.3 Upper limb movement design

4.3.1 Arm movement

The normal range of elbow flexion–extension for adults is -10° – 145° and 0° – 90° for shoulder flexion–extension (Fig. 5). For patients with upper limb hemiplegia, initial training angles must

Table 2
Upper limb assessment scores and classification meanings.

Score	Level	Meaning
1–2 points	Level 1	Indicates that the current posture poses minimal risk and is feasible without prolonged or repeated holding.
3–4 points	Level 2	Indicates some risk after prolonged duration, requiring further research and changes.
5–6 points	Level 3	Indicates that the current posture presents a risk and should be studied and modified after a short period.
>6 points	Level 4	Indicates a relatively high level of risk and requires immediate research and modification.

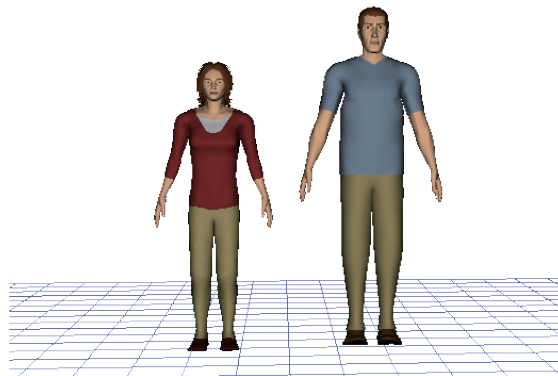


Fig. 4. (Color online) Adult male (P95) and female models (P5) in simulation.

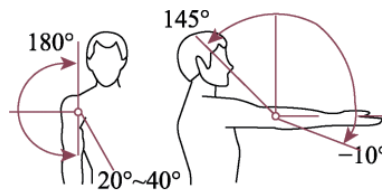


Fig. 5. Diagram of elbow joint flexion–extension range of adults.

not be too large and need to be increased depending on the patient's rehabilitation progress. Excessive driving force and speed pose safety risks owing to the patient's physiological characteristics. In the simulation, we selected two-thirds of the normal range of elbow joint movement, i.e., 0–90°, and two-thirds of the normal shoulder joint movement range, i.e., 0–60°.

4.3.2 Hand movement

The human hand skeleton consists of the wrist bones, metacarpals, and phalanges. The phalanges are interconnected at the metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints. The movements of the finger joints require flexion–extension, adduction, and abduction. Through these joint movements, the human hand grasps, grips, pinches, and performs other fine motor activities. Grasping and gripping use most of the joint movements in the hand, and therefore, hand rehabilitation must be conducted considering these actions. The joints involved in grasping and their approximate movement ranges are illustrated in Fig. 6.

4.4 Simulation and evaluation of single upper limb stretch

We created a digital model of the patient's body to simulate a real task-performing scenario using the JACK software. The patient model performed a single upper limb stretch task under the guidance of a caregiver. The task requires the patient to complete movements within the range of upper limb movements (0–90°). After completing the task, the patient's task behavior was analyzed. The simulated task scenario is shown in Fig. 7, and the RULA scores of different body parts in the movement are presented in Table 3.

The patient scored 2 points for the upper arm and the forearm, 1 point for the wrist and wrist rotation, 5 points for the neck, and 3 points for the trunk, with a total score of 6 points. This indicated that the patient was at risk of musculoskeletal injury during the single upper limb stretch task, and immediate adjustments were required.

4.5 Simulation and evaluation of bilateral upper limb stretch

Using the JACK software, a simple bed model was created to simulate a real task scenario. The patient model performed the bilateral upper limb stretch task under the guidance of a

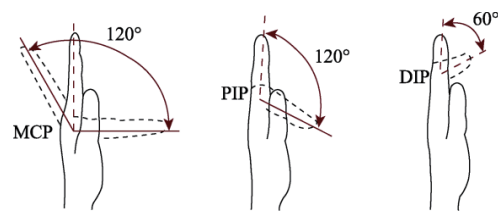


Fig. 6. Diagram of finger joint flexion–extension range of adults.

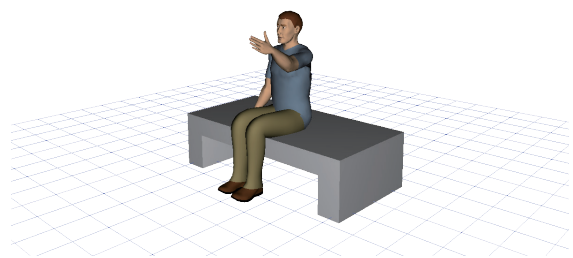


Fig. 7. (Color online) Simulation of single upper limb movement.

Table 3
Scores for patient’s single upper limb movement in simulation.

Task	Upper arm	Forearm	Wrist	Wrist rotation	Neck	Trunk	Load (kg)	Total score
Single upper limb stretch	2	2	1	1	5	3	2–10	6

caregiver. The stretch task required the patient to complete movements within the previously described range of upper limb movements with bilateral upper limbs. The simulated task is shown in Fig. 8, and the RULA scores for different body parts during the movement are presented in Table 4.

The patient model scored 3 points for the upper arm, the forearm, and the trunk, 1 point for the wrist, 2 points for wrist rotation, and 4 points for the neck, with a total score of 7 points. When the patient model is at risk of musculoskeletal injury during bilateral upper limb stretch, immediate adjustments are required.

4.6 Simulation and evaluation of grasping

The patient model performed grasping of objects under the guidance of the caregiver model. Grasping required the patient to complete movements within the previously described range of upper limb movements. The simulated task scenario is shown in Fig. 9, and the RULA scores for various body parts in the movement are presented in Table 5.

The patient model scored 3 points for the upper arm, the forearm, the wrist, and the trunk, 1 point for wrist rotation, and 4 points for the neck, with a total score of 7 points. The patient model had a risk of musculoskeletal injury in grasping objects and demanded immediate adjustments.

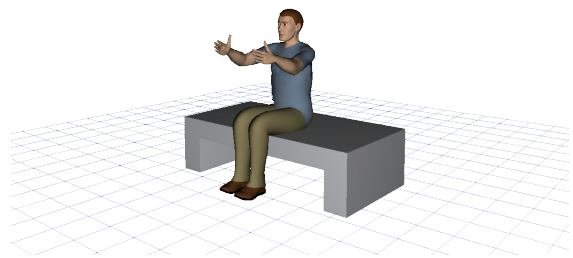


Fig. 8. (Color online) Simulation of bilateral upper limb movement.

Table 4
Scores for patient’s single bilateral limb movement in simulation.

Task	Upper arm	Forearm	Wrist	Wrist rotation	Neck	Trunk	Load (kg)	Total score
Bilateral upper limb stretch	3	3	1	2	4	3	2–10	7

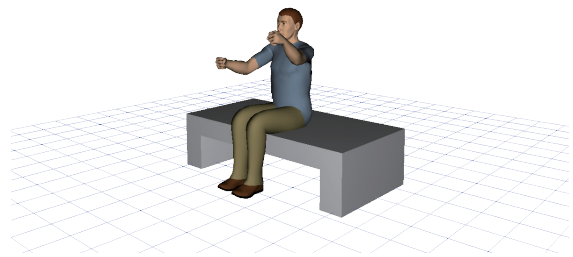


Fig. 9. (Color online) Simulation of grasping of objects.

Table 5
Scores for patient model’s grasping in simulation.

Task	Upper arm	Forearm	Wrist	Wrist rotation	Neck	Trunk	Load (kg)	Total score
Grasping	3	2	3	1	4	3	2–10	7

5. User Needs for Home-based Rehabilitation Robot

To determine the user’s needs for a home-based rehabilitation robot, we interviewed 22 participants in total, including 14 patients with upper limb hemiplegia, three family members of patients, and three rehabilitation robot practitioners (Table 6). The examples of interview content are presented in Table 7.

The interview results were analyzed to explore the relationships, usage habits, and user needs in home-based rehabilitation using NVivo. The analysis was conducted as follows.

- Step 1: Read the transcribed interview data and analyze them on the basis of the literature review results.
- Step 2: Summarize and code the features, and categorize the emotional and physiological needs of the users.

Table 6
Number of interviewees for surveying user needs.

Age	Number	
	Male	Female
18–35 years old	3	3
36–65 years old	2	2
Older than 65 years	2	2

Table 7
Interview content.

Attribute	A (male)	B (male)	C (female)
Age	26 years old	48 years old	77 years old
Occupation	IT expert	Self-employed entrepreneur	Retired teacher
Living environment	Rents an apartment unit with colleagues (nonrelatives)	Lives with family in a three-bedroom, one-living-room unit outside the city center	Lives with husband in a two-bedroom, one-living-room unit inside the city center
Affected area	Single-limb hemiplegia	Upper and lower limb hemiplegia	Upper limb hemiplegia
Cause of paralysis	Cerebral infarction caused by working overtime	Cerebral hemorrhage caused by excessive drinking	Cerebral infarction caused by a fall/tumble
Muscle strength	Grade 4	Grade 3	Grade 3
Daily life	"Drifting" youth in the IT industry, long-term exposure to irregular work habits due to frequent late nights and overtime, leading to an irregular lifestyle. No time for exercise, works under high-pressure conditions, and enjoys researching various emerging technologies.	Owner of a successful micro-enterprise, often attends various business dinners and social events associated with work. Enjoys smoking and drinking. Suffers from high blood pressure and hyperlipidemia.	Has paid attention to physical health since she was a teenager and prioritizes exercise, diet, and psychological balance. Enjoys traveling and hiking, and experiences no life pressure.
Needs	Has a strong sense of independence. Needs more economical rehabilitation treatment options. Hopes to receive diverse rehabilitation models. Values the interactive experience during rehabilitation training.	Focuses on feedback of recovery data, recording the entire recovery process daily. Hopes for intensive upper-limb training since it is a relatively affected area.	Must ensure a sufficiently safe rehabilitation environment during training. Hopes for comprehensive check-ups and monitoring to track health status; requires emergency call assistance to maintain contact with caregivers. Hopes to receive auxiliary therapy for high-level rehabilitation training.

Step 3: Refine the features to explore the user needs based on the primary and refined (secondary) codes.

Step 4: Summarize the content of the primary and secondary codes to analyze the interview data.

The frequency of related needs mentioned in the interviews was compiled using NVivo software (Table 8). The patients showed urgent needs for comfort, fun, visualization, and data

Table 8
User needs summary.

Primary code	Secondary code	Frequency of mention	Example of interview data
Emotional needs	Fun and interaction	20	... have to work overtime and the schedule is irregular, but at least the work is interesting, and exploration is preferred...
	Economical and practical value	14	
	Home-friendliness	11	
	Scientific and accurate method	9	
Physiological needs	Real-time feedback	8	... If there is no feedback, it feels like I have no motivation. It's uncomfortable if the home environment feels as cold as a hospital...
	Fatigue relief	17	
	Pain reduction	13	

feedback from the robot. Therefore, the design of the rehabilitation robot must provide an engaging interaction mode, simple structural principles, and low usage costs.

Hemiplegic patients had strong emotional needs during rehabilitation. Long-term, repetitive rehabilitation training seemed to dampen their enthusiasm for treatment. They valued engaging interactions during rehabilitation, requiring software solutions to address these issues. Smaller rehabilitation robots were more readily accepted by patients undergoing home rehabilitation, as they value their simple design and lower operating costs. However, the safety of independent use of rehabilitation robots remains a major concern for patients and their families.

6. Design and Evaluation of Home-based Rehabilitation Robot

6.1 Design

To meet the basic rehabilitation needs of hemiplegia patients with muscle strength levels 3–4, the robot was designed for home rehabilitation environments and to improve environmental adaptability, ensuring safe operation. The robot provides interactive entertainment through supporting software and has an appropriate appearance as medical-grade equipment, embodying human-centered technology.

To ensure the rehabilitation robot meets the user's needs, the dimensions of the robot were determined on the basis of the P95 data of human upper limbs. The upper arm and forearm lengths for adult males were 338 and 258 mm, respectively, and 302 and 234 mm for adult females. Since there were gender differences in human–machine dimensions, the product length range was controlled between 435 and 485 mm. The hand length and width for adult males were 196 and 89 mm, whereas those for adult females were 183 and 82 mm, respectively. Considering the palm thickness, the width of the male hand was set to 100 mm, and the total length of the hand was set to 220 mm. The upper limb training radius was determined on the basis of human body dimensions, table and chair heights, and the movement range of upper limb joint angles (Fig. 10).

On the basis of user needs and defined human–machine interaction parameters, a robotic model was developed using Rhino 7.0 and rendered in KeyShot (Fig. 11). The robot was designed to meet the rehabilitation requirements of hemiplegic patients with upper limb impairments, offering a safe, comfortable, standardized, and intelligent solution for home-based training.

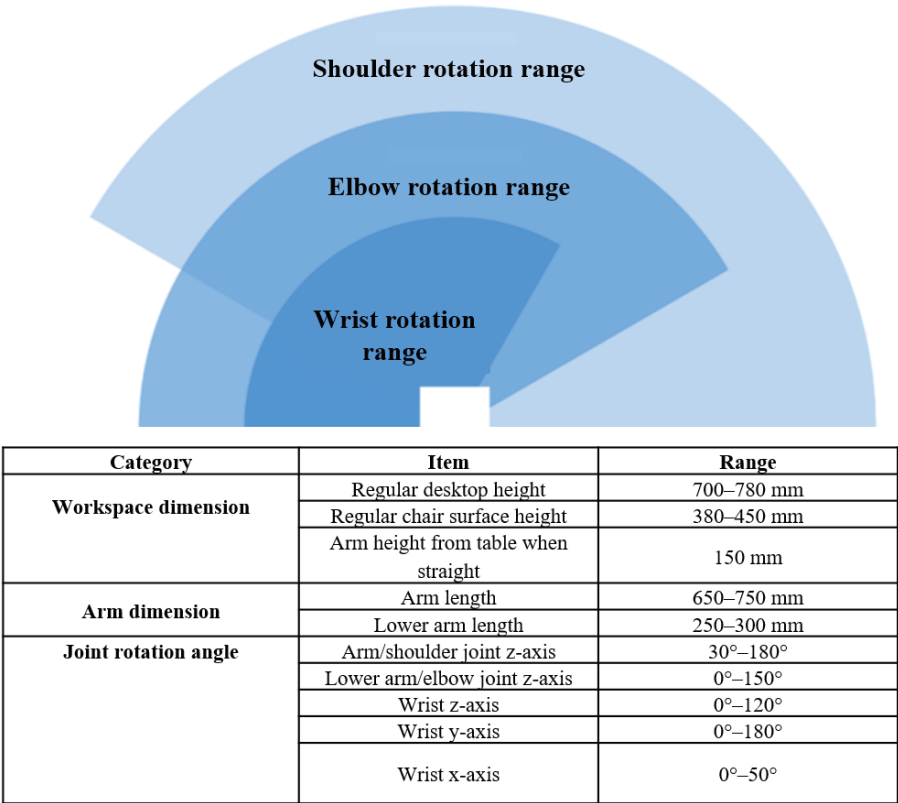


Fig. 10. (Color online) Robot dimensions for upper limb movements for rehabilitation.



Fig. 11. (Color online) Rendering of home-based rehabilitation robot for patients with upper limb hemiplegia.

This desktop-style end-effector robot supports both active and passive control modes. Its main structure secures the patient's forearm and guides upper limb movement along a preset trajectory, enabling coordinated multijoint training of the shoulder, elbow, and wrist. To enhance engagement, the robot system incorporates interchangeable handles, an LED array interactive board, and a gamified software interface, creating a diverse and immersive rehabilitation experience (Fig. 12).

Targeted at patients with muscle strength levels 3 to 4, the robot is optimized for home use. It applies the RULA ergonomic assessment method from JACK virtual simulation to refine training postures and device dimensions, significantly improving user comfort and operational safety. In addition to delivering scientifically effective rehabilitation, the product emphasizes emotional well-being and human-machine adaptability, providing a holistic, user-centered solution for safe and comfortable home recovery. While ensuring scientifically effective training, the robot provides emotional experience and human-machine adaptability, offering a safe, comfortable, and human-centered home rehabilitation solution. The main modules and functions of the robot are presented in Table 9.

6.2 Human-machine interaction

6.2.1 Compatibility assessment

A 3D model of the designed robot was imported into the JACK software for human-machine compatibility assessment in a virtual scenario (Fig. 13). The assessment result showed that the product's dimensions were compatible with the patient's body in seated and standing positions.

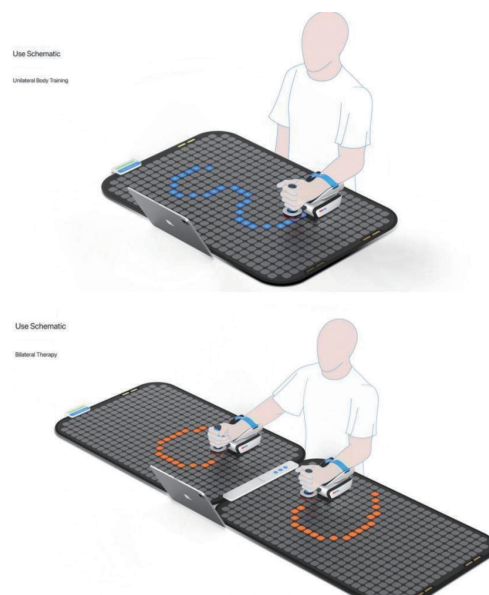


Fig. 12. (Color online) Operation of home-based rehabilitation robot for patients with upper limb hemiplegia.

Table 9
Modules and functions of rehabilitation robot.

Component	Module	Function
Sensors	Primary IR obstacle avoidance system	Obstacle detection
	Auxiliary IR obstacle avoidance system	Primary IR obstacle avoidance
	Laser sensor	Tracking the motion trajectory of the rehabilitation robot
	Bluetooth	Connecting to mobile devices and displays
Actuator/drive	Omnidirectional spherical wheel	High-degree-of-freedom movement and steering functionality.
Protection device	Emergency stop button	Stopping the operation in an emergency
Adaptation device	Wrist strap	Adapting to different sizes of upper limbs (thickness or circumference)
	Telescopic rod/shaft	Adapting to different lengths

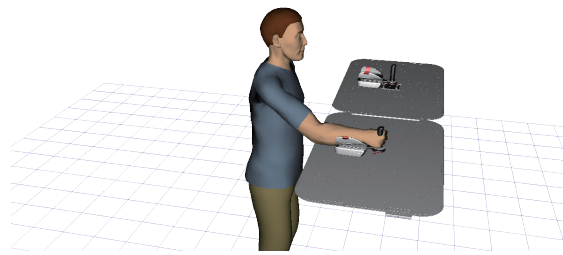


Fig. 13. (Color online) Simulation of patient using designed rehabilitation robot.

6.2.2 Visual field analysis

While using the robot, patients needed to observe the LED board. Therefore, the patient's visual field was simulated and evaluated for effective operation. The visual field for patients when turning their heads to the side and looking straight ahead is shown in Fig. 14. On the basis of the visual field projection, patients were allowed to observe the whole LED board for effective operation.

6.2.3 Comfort assessment

The comfort level of a specific posture or overall body position in using the robot was assessed. During training, patients maintained a standing posture, which was assessed for comfort. The Dreyfuss 2D scale was used as the evaluation metric for comfort, and the results are shown in Fig. 15.

The measured joint angles of a patient in a specific posture were compared to determine comfort ranges using the Dreyfuss 2D comfort scale. The central axis (labeled 0.0) represents the mode (most comfortable value) for each joint angle. The horizontal bars represent the angle value relative to the mode for the patient's posture. The two vertical orange dashed lines indicate the low and high value boundaries of the "comfortable" range. For head flexion, upper arm

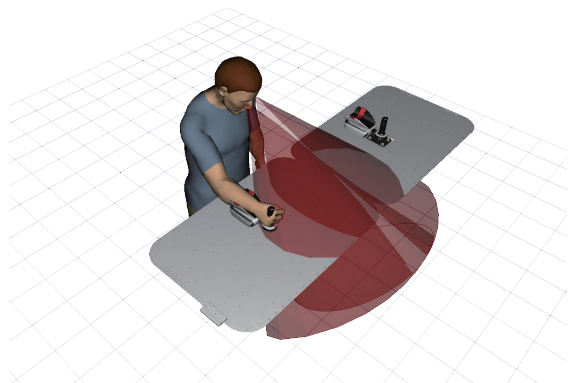


Fig. 14. (Color online) Visual field analysis for patient operation.

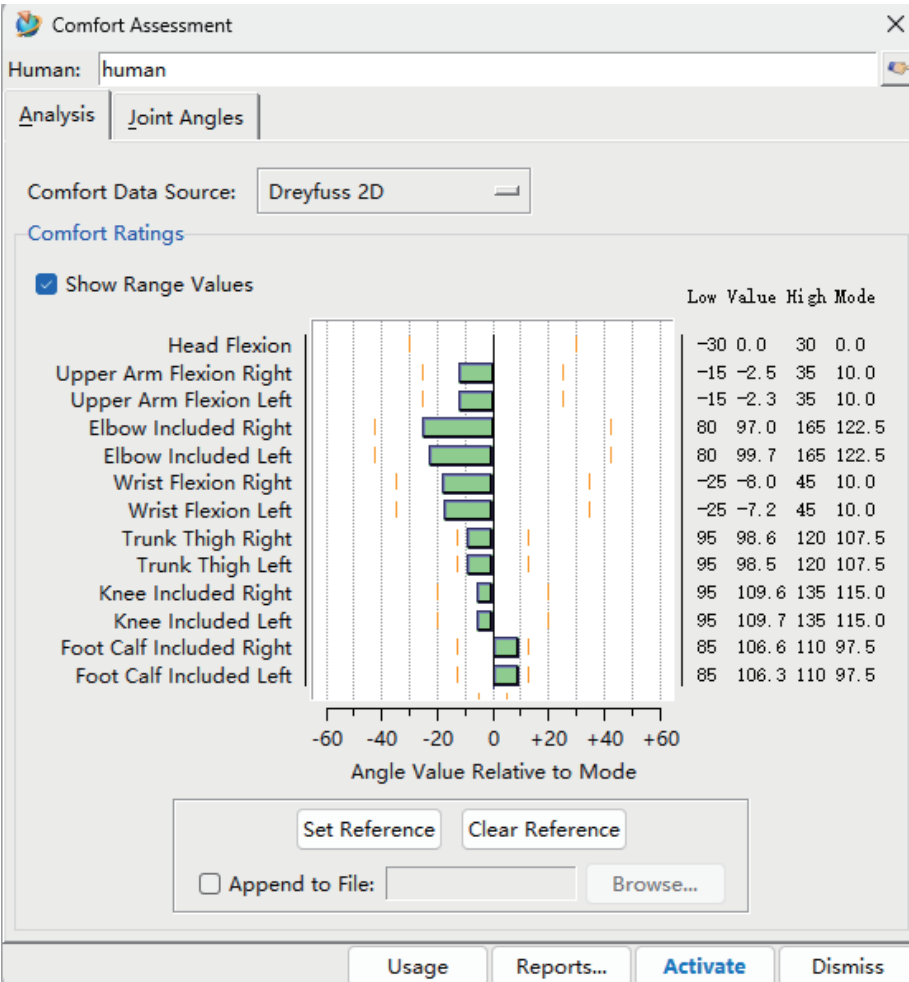


Fig. 15. (Color online) Comfort assessment during patient’s operation.

Table 10
RULA scores for patients undergoing three training operations.

Movement	Upper arm	Forearm	Wrist	Wrist rotation	Neck	Trunk	Load (kg)	Total score
Grasping	0	1	3	2	1	1	<2	2
Single-upper-limb stretch	0	1	1	2	2	2	<2	2
Bilateral-upper-limb stretch	0	1	1	2	2	2	<2	2

flexion, elbow included, wrist flexion, trunk thigh, knee included, and foot calf, the green bar remains entirely within the orange dashed lines. This means that for all 14 evaluated joint angles, the patient's current angle is within the established comfort range. The patient's posture is relatively close to the ideal modal value, indicating a generally neutral and nonstressed posture.

The joint posture analysis results show that the patient's overall body position is stable and ergonomically sound. No joints are at an extreme or near-limit angle, which is associated with discomfort or an increased risk of musculoskeletal strain. The results show that the standing posture is safe and sustainable. As all major joints are within the comfortable range, the risk of MSDs, joint pain, or premature localized muscle fatigue during the training session is significantly reduced. A comfortable posture ensures the patient is not distracted by pain or discomfort. This improves compliance with the training protocol, allowing the patient to focus on the therapeutic movements and maximizing the effectiveness of the robot training. The results validate the robot's adjustability to the patient's anthropometry to maintain a near-neutral posture with minimal effort, and the angles of joint flexion of the patient during training are maintained within a comfortable range.

6.2.4 RULA

Patients operated the rehabilitation robot in standing or seated postures (Fig. 14). RULA was used to assess the postural risks involved in three distinct rehabilitation and training operations (Table 10). The overall RULA score for all three training operations was 2 points, indicating that using the robot for rehabilitation and training was safe, and maintaining these postures for short durations did not pose a significant risk of MSDs.

7. Conclusion

We designed a training robot for the home-based limb rehabilitation of patients with upper limb hemiplegia. We assessed the postural risks of patients performing rehabilitation and training operations with and without robotic assistance, confirming the potential risks of certain postures. The needs of the patients were analyzed through interviews, and the data were categorized and summarized using the NVivo software. Considering human-machine dimensions and design requirements, the robot was designed by incorporating handles, an LED array interactive board, and a game-based interactive system for diverse, immersive, and engaging rehabilitation and training. Human-machine dimensions were determined on the basis of patient body dimensions, ensuring patients' comfort and safety in using the robot. The operation and applicability of the robot were evaluated in terms of human-machine

compatibility, visual field, comfort, and rapid upper limb assessment, verifying the feasibility of the robot in upper limb rehabilitation. This ergonomic and safety validation process was necessary to finalize the physical prototype design and minimize risk. The completed robot prototype needs to be deployed and tested in a clinical setting with actual patients, demonstrating its practical application and effectiveness in improving motor function for upper limb hemiplegia.

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