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Formative Usability Assessment of a Rehabilitative Hand Exoskeleton – Directions for User-Friendly Physical Interfaces

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ABSTRACT

This paper presents a formative usability test study involving eight healthy individuals to identify user-centred criteria and directions for improving the usability of a rehabilitative hand exoskeleton system. The formative usability test was applied as a procedure accompanying the motor learning tests for system validation. The test adopted a qualitative approach combining structured observations during exoskeleton use to complete motor control tasks. The observations were followed by semi-structured interviews immediately after use. Qualitative findings from the formative usability tests revealed issues related to use comfort, wearability, simplicity and perceived safety of the proposed exoskeleton system. Based on these findings, practical design recommendations are provided to enhance the donning and doffing of the device, adjustability of finger connections to accommodate anthropometric ranges, material selection and component layout for improved physical comfort. A finger ring system designed to improve physical ergonomics and usability is introduced. The outcomes of this study are expected to contribute to both the usability improvements of the current system and serve as a reference to the research community in general while developing user-friendly physical interfaces for wearable robotics.

Keywords: Rehabilitation, Exoskeleton, Assistive technologies, Wearable robotics, User requirements, Usability assessment, User-centred design

INTRODUCTION

Stroke ranks as the second most common cause of mortality worldwide and the third most common cause of disability. In Europe, stroke affects 1.1 million individuals and results in 440,000 fatalities annually (Béjot et al., 2016). It is believed that current strategies will be ineffective in lowering these rates in the next years. The major factor is the increasingly ageing population. The number of stroke incidents is predicted to approach 1.5 million by 2025, with the number of persons affected by stroke increasing by 27% between 2017 and 2047 (Wafa et al., 2020). Despite recent major pharmacological advances in stroke treatment, there is no feasible, successful, or permanent medical treatment for stroke. Post-stroke rehabilitation interventions are commonly used in stroke therapy and research is increasingly focusing on the rehabilitation process. The objective of rehabilitation is to improve impaired function and attain the best level of independence feasible within the constraints of chronic stroke-related impairments. Post-stroke physical therapy is a prolonged treatment that requires the involvement of a therapist.

Robot-assisted training is a modern neurorehabilitation approach that has shown efficacy in stroke patients. Robots are commonly utilised by clinicians in stroke rehabilitation because they allow the user to carry out highly repetitive actions precisely. Robotic training with exoskeletons has shown promise in the recovery of motor functions within clinical rehabilitation settings (Prange et al., 2006). Hand exoskeletons, a sub-category of such wearable robotic devices, aim to aid patients in regaining their motor functions. These robotic devices are designed to manipulate the joints of the fingers, primarily for rehabilitation and/or interaction.

Current hand exoskeleton systems pose numerous usability issues due to challenges stemming from the system complications dictated by the complexity of hand kinematics and the diverse tasks it performs (Almanera et al., 2017; Zhu et al., 2022). Size, bulk and weight are among those complications governing most rigid exoskeletons, negatively affecting the devices' comfort, adjustability, portability and wearability (Ferguson et al., 2019). Many systems have low technology readiness levels, posing challenges to acceptability, marketability and home deployment (Martinez-Hernandez et al., 2021).

Engineers encounter difficulties in selecting suitable components and designing control systems to address kinematic complexities, adaptability to various hand sizes, and the need to support different movements and tasks. These exoskeletons require various actuators such as pneumatic, ultrasonic, and DC motors, with considerations for torque, power requirements, and control system design (Kabir et al., 2022). Moreover, post-stroke rehabilitation efforts emphasise functional recovery through motor re-learning, highlighting the importance of effective control mechanisms in robotic rehabilitation (Agarwal & Deshpande, 2015; Levin & Demers, 2020; Marchal-Crespo & Reinkensmeyer, 2009; Sans-Muntadas et al., 2014; Washabaugh et al., 2018).

Despite the technical advancements, the commercial availability of hand exoskeletons remains limited, with most systems at prototype levels. User involvement in the development process is crucial to ensure better usability, satisfaction, and acceptance of such technologies. However, understanding primary user requirements and end-user involvement in the design process is limited (Hill et al., 2017; Kobbelgaard et al., 2021). Issues related to physical ergonomics such as comfort, portability, and wearability are recognised concerns (see, for example, Almanera et al., 2017; Ambrosini et al., 2014; Baltrusch et al., 2020; Majidi Fard Vatan et al., 2021; Martinez-Hernandez et al., 2021), but subjective user perceptions on these aspects and other design requirements are often overlooked.

This paper focuses on identifying user-centred criteria and directions for improving the usability of a rehabilitative hand exoskeleton system. The proposed robotic exoskeleton is a two-degree-of-freedom, fully actuated system. It is designed for the index finger using an optimisation technique that minimises a cost function which is composed of the isotropy measure and the required actuator torque. The rest of the paper introduces the system design and methodology of the formative user evaluation. Recommendations are made to improve the usability of the system design from a user-centred perspective.

SYSTEM DESIGN

Our project focuses on designing an exoskeleton robot specifically for rehabilitating the pinching action by index finger and thumb, which is particularly challenging to regain after a stroke. The design seeks to facilitate the process of motor relearning by implementing a control system strategy and a specific actuation type in the exoskeleton mechanism. We hypothesise that the patient needs various forms of interaction with the robotic exoskeleton during the whole rehabilitation period to maximise motor relearning. The control system can implement kinematic control, interaction-based control, and force control, which may be applied as either an assistive or resistive technique. The exoskeleton can be fully or under-actuated. The under-actuated form facilitates motor variability, which is essential for motor learning. In this study, the exoskeleton is used in the fully actuated form and the control is the admittance type of interaction control. The overall system architecture is presented in Figure 1.

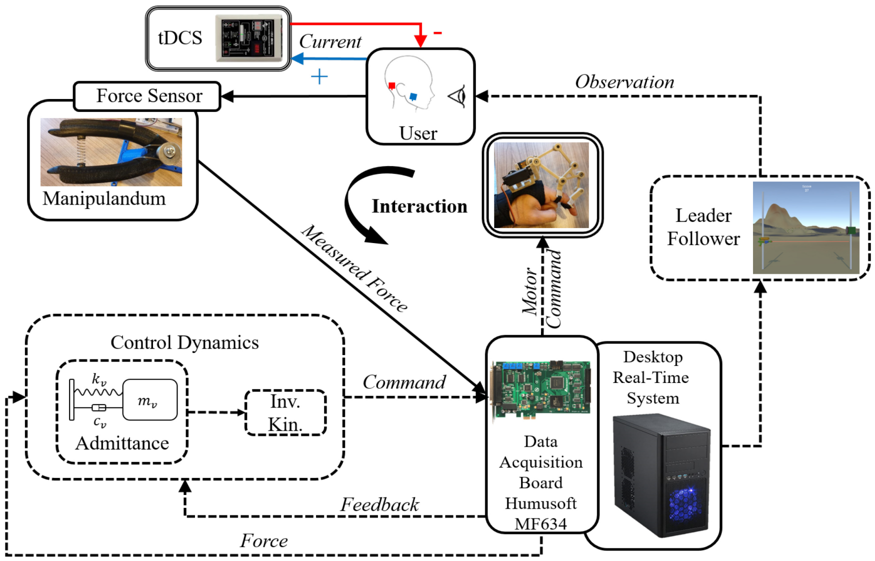

Figure 1: System architecture.

The leader-follower game is the main element of the system. Users produce an upward force in this game by pinching the elastic interface, generating an interaction force. This force drives the avatar of the follower in the upward direction. Likewise, when users let off the interface, a simulated gravitational force causes their avatar to go downward. Users attempt to strike the vertically oscillating target that follows a predetermined pattern. The pattern is composed of the cumulative sum of three distinct frequency harmonics: 0.07 Hz, 0.2 Hz, and 0.25 Hz. The game interface, created using Unity (Unity Technologies, US), is seen in Figure 2.

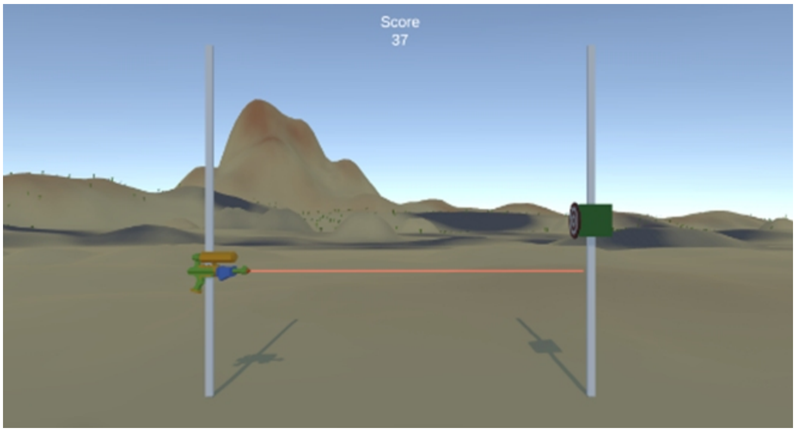

Figure 2: Leader-follower game in unity: the left avatar is the follower, and the right avatar is the leader.

The elastic pinching interface (see Figure 4) connects the user and the game. The device uses a force sensor that quantifies the exerted force by the user's index finger at the tip. The force signal is sampled at 2 kHz and sent to a desktop computer running Simulink® Desktop Real-Time 2021b simulation via a data acquisition device (DAQ) (Humusoft MF634). The exoskeleton controls the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of the index finger. The controller uses an admittance-based interaction control. The controller operates to follow the voluntary finger motions of the participant and uses virtual elastic, damping and inertial forces to restore the finger to its normal position. This system may simply be converted into an assistive or resistive strategy. The control system architecture is given in Figure 3.

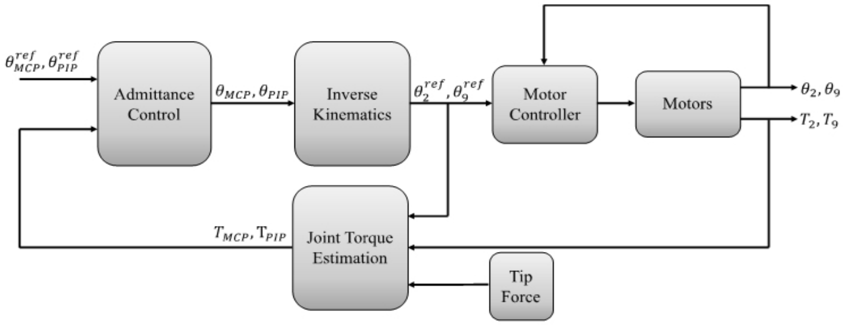

Figure 3: Admittance type control system.

METHODOLOGY

A preliminary user evaluation study was designed to test the current exoskeleton developed for system validation. We planned a user feedback protocol to test the current version of the system with healthy users and evaluate it in terms of ease of use, comfort and perception, and to plan a design revision based on these evaluations. Eight healthy individuals, all sophomore undergraduate students at TED University in Ankara, Turkey, volunteered to participate in the study. All participants signed an informed consent form before the test.

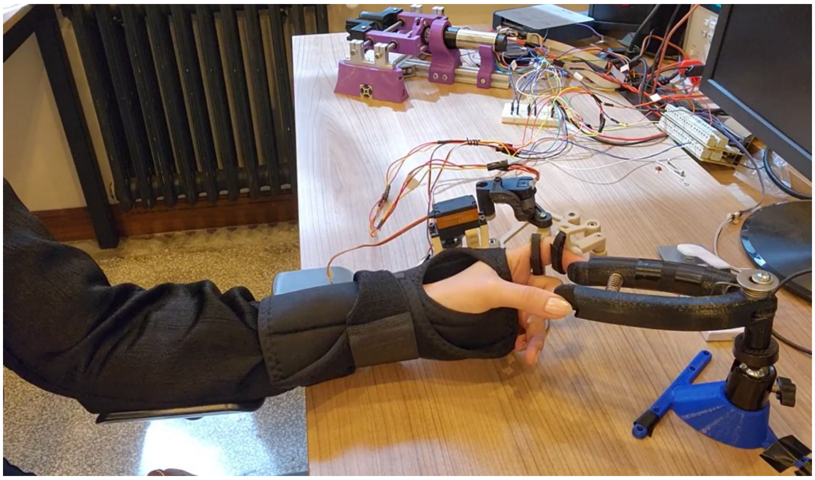

Figure 4: Test setup and video-recording angle.

Test Protocol

User evaluations included observing the participants using the exoskeleton for approximately 15–20 minutes, followed by a short post-test interview. Each test lasted approximately 30–40 minutes including preparation, use and interview. Use and interview sections were video-recorded. Test setup and video recording angle are shown in Figure 4. The post-interview questions were based on the literature review conducted before the tests, which involved four key user dimensions: comfort in use, wearability, simplicity, and perceived safety. Further observations are made for adjustability. Detailed test procedure is presented in Table 1.

FINDINGS

Three hours of videos were recorded during the use and interview phases of the eight test sessions. These recordings were watched by one researcher (industrial designer specialised in user research) to identify and document the usability issues observed and stated by the participants. This section presents the identified issues regarding comfort in use, wearability, simplicity, and perceived safety.

Table 1. Test procedure.

Test phase	Duration	Activities
Preparation	5–10 minutes	1. Participant reads and signs the consent form. 2. Participant is introduced to the setup and the test procedure as follows: where and how to sit, introduction and a short demo of the game. 3. Participant's arm is placed on the elbow rest and the placement and the controller are adjusted.
Use and observation	15–20 minutes	4. Participant plays the game without the exoskeleton. 5. Researcher helps wear the exoskeleton, and the participant plays the same game with it. 6. Participant is asked to take off the exoskeleton without help. *Observed interactions:* Difficulties when donning and doffing; Placement of the fingers and wrist inside the device; Stability of the device and if the participant wants to fix it; If the device affects the hand posture; Difficulties while taking the device off alone
Post-interview	5–10 minutes	7. Open-ended questions are asked of the participant. *Interview questions:* How did you feel using the exoskeleton, and why? What are your comments on its comfort in use? Have you encountered any difficulties while taking it off, can you show it on the device? What are your comments on its general look and structure? Do you think it is safe to use it, and why? Do you have additional comments or suggestions? 8. The participant plays the game one last time without the exoskeleton to complete the performance test, and the procedure is concluded.

Comfort in Use and Wearability

The vast majority of the findings point out issues with use comfort, including the method for placing and fastening the finger pieces, weight and balance of the exoskeleton, and the material.

- The current design utilises a standard-size, 3D-printed finger placement form. These finger pieces are fastened to the middle and proximal phalanges via Velcro straps attached to two protrusions on semi-rings. During use, these protrusions are observed to be rubbing against the middle finger, causing physical discomfort and limiting the movement of the user.
- The design of the finger piece does not accommodate the anthropometric variety in finger size. This issue is tried to be overcome by fastening with the Velcro straps, but the lack of a firm finger grip creates gaps between the phalanges and the finger pieces. These gaps were filled with foam pieces, which frequently came loose, disrupting the testing procedure.
- The pulling force on the middle phalanx led to discomfort and redness on the skin. This was also expected to be prevented with an additional foam layering between the finger and finger piece.
- The skeleton part of the device is lightweight since it is made of 3D-printed plastics. However, the motor and actuator mechanism creates load

and discomfort on the wrist and arm during use (Figure 5). Half of the participants expressed discomfort after nearly 15 minutes of use. Although they didn't think the pain and fatigue were unbearable, the impact could be worse for patients during longer rehabilitation sessions.

- Since comfort was not a priority in the current design, the robotic mechanism was attached to a standard wrist splint. Although it is easy to put on the splint, fastening it requires rotating the hand and wrist around their own axis. Some participants found this uncomfortable due to the weight of the mechanism. Additionally, some reported that the synthetic material of the splint causes sweating after use.
- During the tests, a researcher helped don the device, and the participants were asked to take it off themselves. Although doffing the device is relatively easy, correct placement and fastening of the finger pieces took time and effort during donning the device (Figure 6).
- Wearability is related to comfort in longer use as much as it does to ease of donning and doffing the device. The above-mentioned issues with weight balance, material and form are factors affecting wearability.

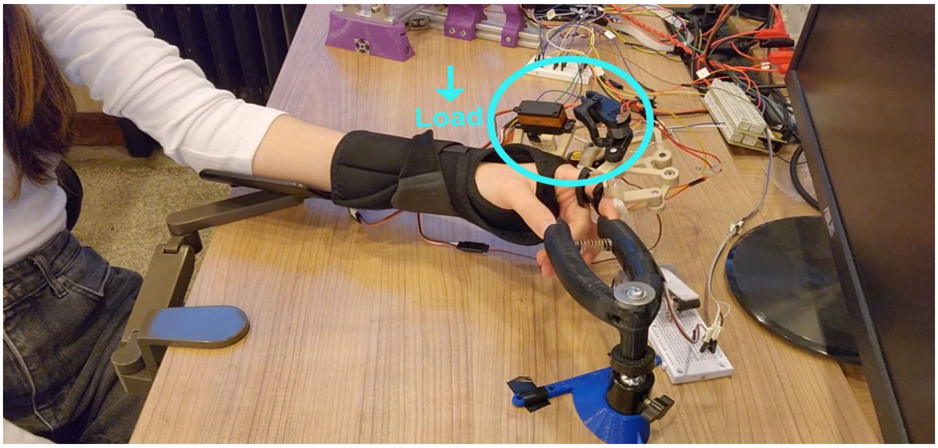

Figure 5: The weight of the motor and actuator creating load on the wrist and arm.

Figure 6: Donning with help (left) and doffing without help.

Simplicity and Perceived Safety

Other issues identified are related to the perception of the device rather than physical interaction:

- Participants drew attention to the visual issues, particularly the fully open structure of the skeleton, motor and actuator mechanism, and the fact that the cable connections are disorganised. Some of the phrases they used to describe the visual language of the setup are: "too mechanical", "messy", "exposed", and "difficult to understand".
- Some participants emphasised the disorderly look of the protrusions of the finger pieces to fasten the Velcro straps.
- Despite the critique of the look, some participants stated that these were their first impressions, and it did not matter as much while using it because they discovered that it was not as scary as it looked and while playing the game they no longer looked at the skeleton.
- A few participants stated that the sudden finger pull of the skeleton at the beginning of the test felt unsafe. Although it is not part of the exoskeleton design, it has an impact on the user experience.

ACTIONS FOR IMPROVEMENT

Focusing on comfort and wearability, we prioritised the development of a ring system for easy donning and doffing, secure fastening, and preventing discomfort. The system consists of individual rings worn in fingers, inserted in the nests located on the skeleton by leveraging material flexibility and interlocking tabs (Figure 7). We have completed first iterations and currently adapting the nesting piece to the exoskeleton.

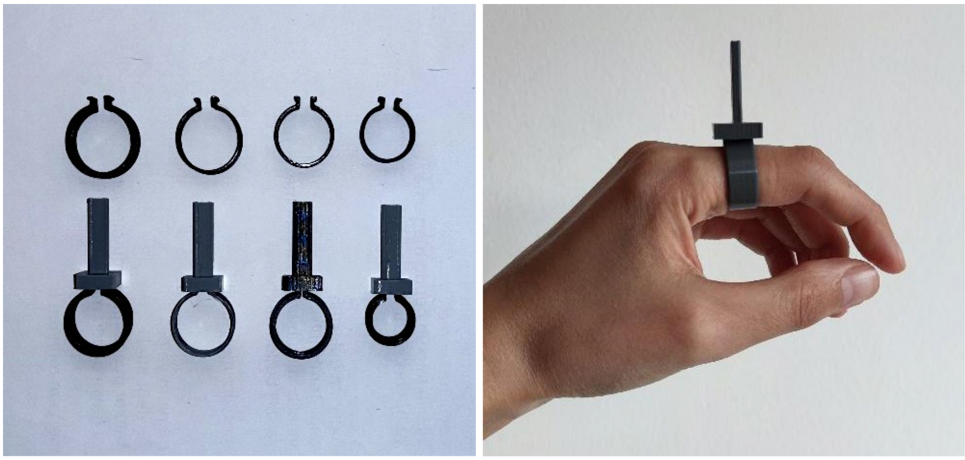

Figure 7: First iterations of the ring system design.

As adjustability to various hand sizes is vital, the following steps will include designing a set of ring components based on an existing data set for hand anthropometry (Cakit et al., 2012). The data set will be used to develop an ergonomic design approach combining 'design for extremes'

(5th percentile female and 95th percentile male) and 'design for adjustable range' strategies to accommodate the largest possible population (McCauley, 2012).

Further improvements can be made for a balanced distribution of the weight of the robotic setup to mitigate the load and discomfort on the wrist and arm. In addition to relocating the motor and actuator mechanism without obstructing the proper functioning, it is possible to place an adjustable base to the setup to support the wrist and minimise the load of the exoskeleton.

The standard wrist splint will be replaced by a custom-designed, fingerless guard glove to mitigate sweating and weight-pulling. A breathable material such as knitted polyester can be used as the main material, supported by 3D-printed attachments to fasten the exoskeleton. Polyester is widely preferred in sports gear due to its ability to facilitate sweat dispersion.

Visual simplicity and acceptability are important concerns raised by rigid exoskeletons as also emphasised in the literature. Being a rehabilitation device, system performance is naturally prioritised in the design and development of wearable rehabilitation robots, therefore device form is often overlooked. Although the skeleton structure cannot be interfered with simply based on visual concerns, disguising, collecting and orderly connecting the cables to the system components and power source can significantly contribute to the visual simplicity. Finally, replacing the current finger pieces with the newly developed ring system design is expected to improve the aesthetic perception of the device.

CONCLUSION

This paper presents our findings of the formative usability assessment of a fully actuated rehabilitative hand exoskeleton. The user evaluations were conducted simultaneously with the motor tests carried out with an initial setup. Early involvement of users helped identify major usability problems that can be solved and integrated into the upcoming system revisions. This required the collaboration of a team of engineers and industrial designers, creating opportunities for the improvement of the user-friendliness of the device without compromising its performance. Future work will include integrating the planned changes into the new prototype iterations, and structured usability tests to assess comfort, wearability and perception of the device.

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