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Development of a Sensor-Based System for Stroke Rehabilitation: Home-Based Dual-Task Training for the Paretic Arm

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Abstract: Aim and focus of the research was to develop a prototype system to increase training intensity of the paretic arm and functional cognition for stroke patients through home-based rehabilitation. The key feature of this system is its ability to deliver home-based dual-task training with haptic feedback for grasp, addressing the high priority of grasp function in upper extremity rehabilitation. The prototype consists of a gamified training application and specifically developed input devices. It is the first sensor-based rehabilitation system to incorporate neutral hand positioning, increasing comfort during use and offering physiological benefits. Real-time feedback on cognitive and motor performance is expected to encourage patient engagement. The prototype received positive feedback from experts regarding its potential effectiveness in a preliminary evaluation with seven participants. In future research, a pilot study and real-world testing with the target group will be necessary to objectively verify whether the use of the prototype increases training intensity.

Keywords: home-based rehabilitation, dual-task training, neutral posture, process-based cognitive training, upper extremities, paretic arm, self-training, exergames, grasp, stroke patients

1 Introduction

A paretic arm is a common consequence of stroke, severely affecting quality of life. Beyond motor impairments, nearly 80% of stroke survivors experience cognitive decline [1], further affecting quality of live.

A promising approach to addressing both motor and cognitive challenges is dual-task training, which integrates motor and cognitive exercises. It outperforms single-task motor and cognitive training in improving upper extremity function in chronic stroke patients [2] and enhances global cognitive function [3].

Responsiveness to upper limb rehabilitation for stroke patients is proportional to training intensity [4]. Despite this, access to rehabilitation, and consequently, training intensity, remains limited, particularly after the acute phase of a stroke [5]. To bridge this gap self-training is a possibility, where patients receive instructions for exercises to complete at home.

However, traditional self-training faces two key challenges: insufficient feedback and a lack of motivation. Feedback on motor performance is essential, since impaired proprioception after stroke makes it difficult for patients to identify how to improve their movements [6]. Moreover, low motivation is the primary barrier to adherence in self-training regimens for stroke survivors [7].

Gamification is a promising approach to address both issues. Research has shown that, for chronic stroke patients, gamified applications in upper extremity rehabilitation are more effective than traditional written self-training plans [8].

A possible solution to increase training intensity and provide movement-feedback is a sensor-based rehabilitation system with a gamified application for self-training, potentially improving recovery.

To address the importance of grasping in stroke rehabilitation [9] and the sensory deficits following stroke, a handheld device capable of providing haptic feedback on grip could be beneficial.

The question arises as to what shape would be most suitable for such a device. Cylindrical devices that offer feedback on grip force have already been implemented [10,11]. Yet, their design requires the finger flexor muscles to remain in a shortened position, which could long term contribute to muscle contracture [12].

Given that a flexed resting hand posture is already a common characteristic of upper extremity hemiparesis in stroke patients, an alternative device shape may be more advantageous for individuals with moderate hemiparesis.

A more feasible solution could involve neutral positioning, where the joints are neither in extension nor flexion [13]. This approach not only avoids the risks associated with prolonged flexion but also enhances overall comfort [13].

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2 Design phase

Incorporating feedback from professionals in cognitive and stroke rehabilitation during development was essential to ensure the prototype met the target group's needs, especially given the interdisciplinary nature of stroke rehabilitation. Their feedback was continuously implemented through an iterative development process.

Initially, two gamified cognitive training concepts for the prototype's application were developed, one based on process-based cognitive training and the other on worksheets used in occupational therapy. These concepts were presented to a psychologist to determine which is best suited. The psychologist preferred the process-based cognitive training approach and gave feedback on integrating additional cognitive functions and optimizing the cognitive difficulty settings.

A subsequent interview with an occupational therapist was held to validate the cognitive training concept and to discuss the motor requirements. Based on both expert interviews, the concept was modified.

After the technical implementation of the prototype, an interview with two occupational therapists was held to gather feedback on the prototype, regarding the haptic properties of the input devices and the implementation of the motor requirements of the control system. Suggestions for adjustments to the controls and haptics were documented.

Figure 1: Input device with neutral positioning of the hand. Left: Device with the cuffs, Right: Device with tilting base.

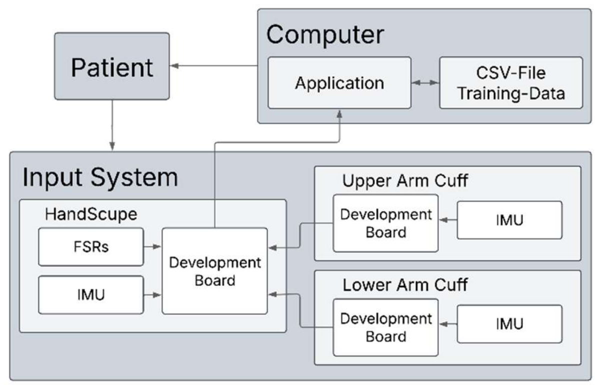

Figure 2: System diagram

3 System description

3.1 Hardware

The developed input devices consist of two handheld devices and two cuffs (see Figure 1) all equipped with inertial measurement units (IMU). For patients with moderate hemiparesis, the HandScupe [14], a medical device for maintaining the hand in a neutral position, was modified by integrating sensors (see Figure 1). Based on expert feedback, a removable tilting base was created for the controller to make wrist movement more comfortable during wrist mobilisation.

Additionally, a cylindrical device (Ø = 4 cm, length = 12 cm) was developed for patients with better motor control in the affected arm. This device supports training of the cylindrical grip and pinch grasp, which are vital for activities of daily living (ADLs) [15].

To detect grip behaviour, Force Sensitive Resistors (FSRs) were incorporated due to their compact design and cost efficiency. Arm movements are captured using IMUs (see Figure 2), offering a simpler alternative to camera-based tracking systems and avoiding issues related to camera field of view.

3.2 Signal processing

For the application, various motion-based control options can be selected and adjusted according to the patient's abilities. For the grasp-based control option, the FSR data remains unprocessed, as the raw values provide an adequate estimation while minimizing computational demands.

The absolute orientation of the sensors is represented through quaternions to prevent the gimbal lock. This is necessary for the tilt – and hand-position based control option. To estimate orientation relative to the patient's facing direction, a short initialization phase is required to determine the device's global orientation and store it as an offset.

Additionally, control may be based on the hand's local position, referenced by the cuff's absolute orientation (see Figure 2). The local position of the hand was determined using model-based tracking with direct kinematics.

For patients with good motor control in the affected arm, a movement-speed-based control option is offered. In this approach, peaks in movement speed are detected and compared across three directions. The process begins by high-pass filtering the acceleration data from the handheld devices using a third-order filter with a 0.5 Hz cutoff. The filtered signal is then integrated to compute speed, filtered once more, and signal amplitude is squared. Peaks are subsequently identified using preset thresholds and wait times.

The processing parameters were optimized through visual inspection of the signals and comparison with camera-based tracking data. The cutoff frequencies were determined by examining the Fourier transform of both processed and unprocessed data. In addition, heuristic adjustments to the threshold values and the implementation of a minimum interval requirement ensured reliable peak detection.

3.3 Gamified application

The computer application was created using the Unity game engine by Unity Technologies. In total, there are five separate training modules implemented. Overall, the application is visually designed as a small workshop, where the patient performs various tasks to build a birdhouse (see Figure 3). All modules incorporate process-based cognitive training (see Table 1).

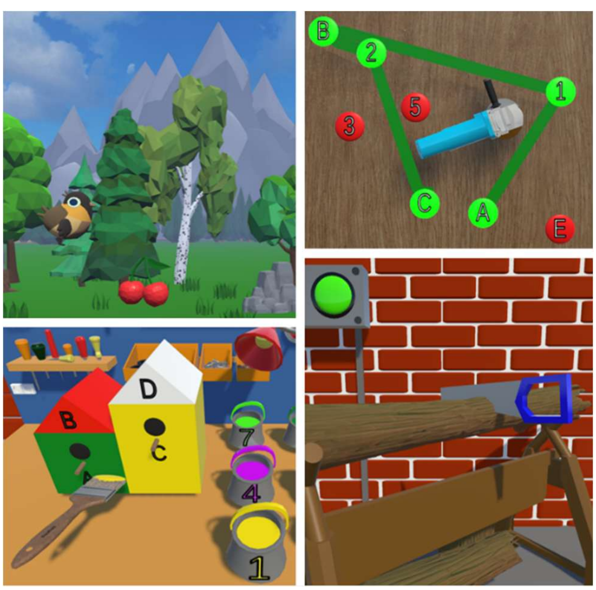

Figure 3: Clips from different training modules of the application

The application offers multimodal feedback, including both visual and auditory elements, providing knowledge of performance and results. A high-score system is implemented, with scores preserved across training sessions. Data from each session, such as gameplay duration, daily high scores, usage duration, and current difficulty settings are recorded.

Table 1: In the application implemented training modules

Modules	Task/Test	Functions
Sawing	Go/No-Go Task	Inhibition
Sanding	Trail Making Test	Visuomotor coordination Cognitive Flexibility
Drilling	Corsi Block Tapp	Visuospatial sketchpad
Painting	Digit Span Task	Phonological loop
Flying	Switching Task	Cognitive Flexibility

4 Preliminary Evaluation

After optimizing the prototype based on feedback from the product development phase, a preliminary evaluation was conducted using both a questionnaire and semi-structured interviews. As the evaluation is preliminary, it is subject to several limitations (see Section 4.1). Seven professionals in cognitive and stroke rehabilitation (two psychologists, four occupational therapists, and one physiotherapist) participated. Each session included a brief presentation of the prototype, followed by a demonstration. The questionnaire employed a five-point Likert scale with options ranging from "strongly agree" to "strongly disagree" (see Figure 4 and Table 2). Additionally, oral questions were posed during the sessions to gather qualitative feedback and insights for further development.

Table 2: Key Questions from the Questionnaire

Number	Question
Q1	Would you recommend the prototype for home-based therapy?
Q2	Do you think the use of the prototype would increase compliance for self-training?
Q3	Do you think that the prototype can effectively supplement motor training for some stroke patients?
Q4	Do you think the prototype can support cognitive training for some stroke patients?

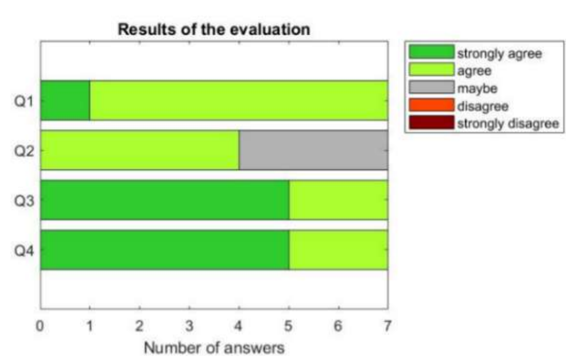

Figure 4: Answers to key questions

4.1 Limitations of the Evaluation

Several limitations of the preliminary evaluation must be considered, as they may have influenced the findings. One key factor is the small sample size of seven participants which limits the generalizability of the findings. Additionally, some of the experts surveyed were also involved in providing feedback during system development. Due to experts' varied availability, evaluation sessions were limited to 30–60 minutes. Another limitation is the focus of the preliminary evaluation solely on professionals, excluding input from the target group.

5 Results and Discussion

A prototype system was developed to increase training intensity of cognitive and motor rehabilitation for stroke patients. The functional protype received positive feedback regarding its potential effectiveness in a preliminary evaluation (see Figure 4).

The qualitative feedback from five of the seven experts showed that the application settings could be too complex for patients. Initially, numerous settings were implemented for adaptability to individual needs. An automatic difficulty adjustment based on patient performance could improve usability.

The cognitive training modules were based on standardized cognitive tests to ensure an evidence-based approach. However, using these tests for post training diagnosis may lead to inaccurate results.

Feedback on increasing training intensity was mixed (see Figure 4). Experts noted that gamified digital training may not suit every stroke patient, particularly due to age-related digital literacy challenges. One promising strategy to increase training intensity is integrating a calendar function into the application to remind patients to train.

6 Conclusion

The developed prototype could form the basis of a cost-effective, home-based, dual-task training system that supplements conventional rehabilitation and improves recovery results in terms of paretic arm functionality and executive function. Promising results were obtained from the preliminary evaluation, although several limitations must be acknowledged (see Section 4.1). Future work must include extensive real-world testing and a pilot study with the target group to assess whether the prototype increases training intensity and improves physical and cognitive functionality. Additionally, the prototype should be refined based on target group feedback.

Author Statement

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