A User-centred Design and Feasibility Analysis of the WiGlove - A Home-based Rehabilitation Device for Hand and Wrist Therapy after Stroke

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***Abstract*—Stroke survivors often experience deficits in their hand's motor function, which can greatly impact their ability to perform activities of daily life. Home-based rehabilitation with robotic devices has been shown to improve the recovery of hand functions. The WiGlove is a home-based robotic orthosis that has been developed using a user-centred approach to offset the hyperflexion in the hand and wrist of hemiparetic stroke survivors. It facilitates training the distal joints of the upper limb at home while performing activities of daily life or playing therapeutic games on a tablet. In a formative evaluation, stroke therapists positively rated the WiGlove's usability and provided feedback which assisted in improving its design. Additionally, the preliminary results of a feasibility analysis at a stroke survivor's home showed evidence of the WiGlove's usability and acceptance with a noticeable impact on reducing the tone in the impaired hand.**

***Keywords*—Stroke rehabilitation; Robot-aided rehabilitation; Home-based therapy; Hand-wrist orthosis; Feasibility.**

I. Introduction

Stroke often results in hemiparesis, where the survivors experience motor function deficits on one side of their body. Hemiparetic stroke survivors often experience weakness and abnormal synergies such as excessive involuntary flexion (hyperflexion) in their hand which severely affects their ability to independently perform Activities of Daily Life (ADL) [1]. While rehabilitation is prescribed to regain the hand's functions, the traditional approach of one-to-one physical therapy limits the amount of training due to factors such as the availability of therapists' appointments. Robot-aided rehabilitation techniques have shown the potential to act as a valuable companion to therapists, offering the ability to provide high repetitions and objective measures of assessments without requiring their presence [2].

Robotic devices that allow stroke survivors to independently perform exercises at home at a flexible schedule can lead to an overall increase in training intensity and associated recovery [3]. Home-based rehabilitation devices enable therapists to remotely monitor the progress and use their expertise to help more stroke survivors which is invaluable in times like the COVID-19 pandemic. While a variety of robotic devices have been proposed for the neurorehabilitation of the hand [4][5][6][7], the majority focus only on training either the wrist or the fingers but not both [8], neglecting the synergy between them. Most of them are only suitable for use in a clinical environment, resulting in limited training durations. Only SCRIPT Passive Orthosis (SPO) [1] was found to be suitable for training independently at home.

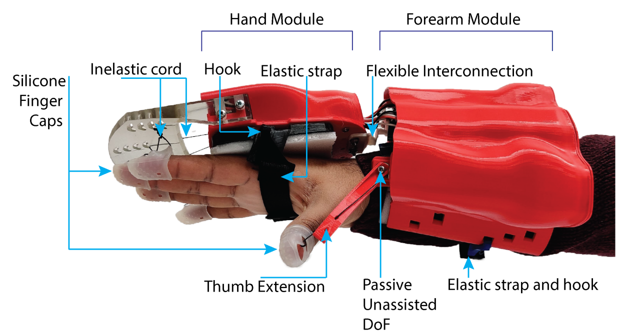

Figure 1. WiGlove.

SPO is a passive orthosis that allows stroke survivors to perform hand and wrist exercises. Developed in a European Framework 7 project, it is a part of the SCRIPT system that includes interactive games and a back-end system for clinical monitoring. While a study involving 23 stroke survivors validated SPO's feasibility, it also identified several functional and usability shortcomings [1][9]. Usability is one of the significant user requirements that affect the acceptance of such devices [10].

Hence, the overarching aim of the research presented in this paper aims to design and develop a home-based rehabilitation device for the hand and wrist that addresses the limitations of SPO through a user-centred design approach (UCD). Beginning with the features of the WiGlove in Section II, this paper focuses on discussing the methods (Section III) and findings (Section IV) of its formative usability evaluation with stroke therapists and presents preliminary results from the feasibility study conducted at a stroke survivor's home.

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Figure 2. Image showing a stroke survivor's hand with hyperflexion in the fingers being offset by WiGlove.

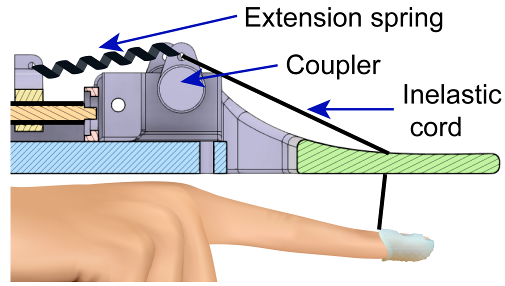

Figure 3. Extension assistance mechanism.

II. WiGlove

In a user-centred design process, an extensive review of the state of the art including task analysis and user studies by the SCRIPT consortium was used to compile a comprehensive set of user requirements for such a device [10]. Building on the knowledge from SPO, the WiGlove was designed to satisfy these requirements. The WiGlove is a passive dynamic orthosis that assists hemiparetic stroke survivors in performing flexion/extension exercises with their fingers and wrist while performing ADL or playing therapeutic games on a tablet. In addition to providing support, a dynamic orthosis also helps to articulate the joint. The WiGlove consists of a forearm and a hand module coupled using a flexible interconnection to allow for ab/adduction of the wrist reducing the risk of hypertonia from non-use. It uses elastic straps with hooks for easy don/doffing of the device with the unimpaired hand. Furthermore, all the surfaces of the device that come in contact with the body while wearing are lined with thermoplastic polyethene foam to ensure comfortable soft interaction. Since the modules are 3D printed, it allows the user to customise their appearance which could enhance its acceptance.

A. Extension assistance

The WiGlove uses extension springs as passive actuators to assist with the extension of the wrist and fingers to a more neutral position from a fully flexed position (Figure 2). This allows the stroke survivors to voluntarily perform flexion against the resistive force of the springs. This mechanism where the device remains passive during training is adopted due to its reduced safety concerns compared to its active counterparts.

The wrist's assistance mechanism is located on the forearm module from which the spring force is transmitted to the joints using an inelastic cord that is attached to the hand module. Similarly, each finger is individually assisted, where the cord is attached to the distal segment of the finger in a base-to-distal configuration that eliminates the concerns of misalignment between the centres of rotation of the fingers and the device. This also ensures that the ab/adduction of the fingers is unrestricted. The cords are guided through an extension structure and are attached to the fingers using a silicone digit cap that allows for tactile feedback while grasping objects (Figure 3). The extension structure is transparent to permit visual feedback while training. The thumb's mechanism is attached to the forearm module to reduce the weight acting on the hand. Additionally, it has a passive joint to facilitate the thumb's ab/adduction, which is essential for its opposing action while grasping.

B. Feedback sensors

The spring in each assistance module is attached to the respective inelastic cord through a coupler that rotates about the shaft of a rotary potentiometer. When a finger or the wrist is flexed, the inelastic cord exerts a torque on the coupler which rotates the potentiometer's shaft. This generates an analogue output voltage that is interpreted by the microcontroller to measure the flexion/extension angle of the wrist and individual fingers. Furthermore, the microcontroller used to interpret the joint angles contains a built-in 9-axis Inertial Measurement Unit (IMU) which is used to estimate the arm's posture.

C. Tension adjustment

Based on the degree of hyperflexion experienced by the user, springs of appropriate stiffness can be used. However, the amount of assistance required could change during training with recovery. Therefore, the WiGlove has a motorised tension adjustment system that increases or decreases the free length of a given spring. This allows the user and the therapists to modulate the assistance so that the user is adequately challenged during training using a slider interface on a touchscreen tablet.

D. Wireless connectivity and tablet interface

Unlike SPO which is tethered, the WiGlove is a wireless device and as such does not require the user to be at a specific location. This allows the user to train in different places in their home. The microcontroller transmits all the data to a touchscreen tablet through Bluetooth 4.0. This allows both therapists and users to monitor the performance including the range of motion (RoM), number of repetitions, training duration, etc. It also allows the user to interact with therapeutic games on the tablet while training with the WiGlove to enhance motivation. It can be charged using a micro-USB cable.

III. Methods

In a previous study, a comparative evaluation of the WiGlove and SPO in a counterbalanced, within-subject experiment involving 20 healthy participants, showed statistically

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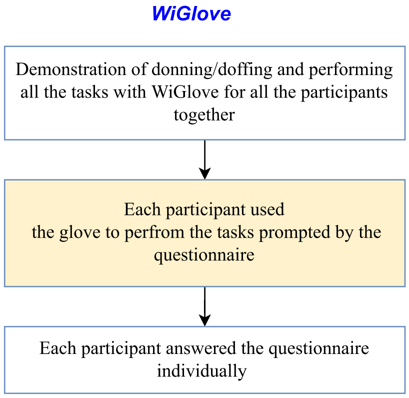

Figure 4. Experiment flow.

significant evidence of the WiGlove improvements over the SPO in the following usability aspects: ease of donning and doffing, ease of adjusting the assistance, unrestricted natural DoF, suitability for ADL and perception of aesthetics, wireless operation and safety [11]. Building on this preliminary validation, further usability evaluation was conducted in two stages with stroke therapists and stroke survivors as follows.

A. Formative evaluation - Stroke therapists

The objective of this phase was to leverage the expertise of therapists with experience in post-stroke rehabilitation to improve the WiGlove's usability and safety before introducing it to stroke survivors. This study was approved by the University's Ethics Committee (Ethics protocol number: aSPECS/ PGR/ UH/ 04896(1)).

1) Study protocol: In this in-person heuristic evaluation process, stroke therapists $(N = 6)$ from the Luton and Dunstable hospital, UK used the WiGlove and assessed its usability. Firstly, a demonstration of using the WiGlove was provided to all the participants (Figure 4). Following this, each of them used the device and performed a set of tasks designed to help evaluate the above-mentioned aspects of usability, similar to [11].

They involved don/doffing the different modules of the device in a specific sequence, performing ab/adduction of the wrist to ensure that the device does not block this degree of freedom which could lead to hypertonia, and adjusting the amount of extension assistance, etc. To assess the WiGlove's suitability for performing ADL while wearing it, three different grasping tasks, namely palmar pinch (key), cylindrical grasp (bottle) and a spherical grasp(ball) were included (Figure 5). These precision (palmar pinch) and power (spherical and cylindrical) grasps are significant to perform ADL [12].

(a) Palmar Pinch (Key). (b) Cylindrical grasp (bottle). (c) Spherical grasp (bottle).

Figure 5. Grasping Tasks

2) Data Acquisition: Upon completing the tasks, the therapists individually gave feedback using a 7-point Likert scale questionnaire. Each question related to the individual tasks that they performed. For example, the following is one of the questions that requested the participant to rate the ease with which they could perform the cylindrical grasp.

How easy was it to grasp the bottle while wearing the device ?

	1	2	3	4	5	6	7	
Very Difficult	○	○	○	○	○	○	○	Very Easy

This approach was adopted since traditional usability scales such as System Usability Scale (SUS) are tailored for end users (stroke survivors in our case) and hence was rendered unsuitable for this study. Additionally, open-ended questions were also used to record their thoughts in a more detailed and descriptive manner on the WiGlove's suitability of ADL, don/doffing and safety. Each participant took approximately 15 minutes to answer the questionnaire. This approach provided invaluable context to their Likert scale scores and helped to better address their concerns in improving the WiGlove's design.

B. Feasibility Study - Stroke Survivors

Having incorporated the therapists' feedback, the revised WiGlove is undergoing a 6-week evaluation at a hemiparetic stroke survivor's home. The participant uses the WiGlove to perform flexion/extension exercises without the supervision of a therapist. This study was approved by the University's Ethics Committee (Ethics protocol number: aSPECS/ PGR/ UH/ 05084(1)).

1) Study Protocol: The participant was recruited using flyers placed in the stroke unit of the Luton and Dunstable Hospital. He is a 78-year-old male, who experienced strokes twice 15 months ago, resulting in left-sided hemiparesis. It is evidenced by the excessive tone in the hand that resulted in a clenched fist (as seen in Figure 2) which prevented the participant from grasping any boxes or pegs in Box and Block(BnB) and Nine Hole Peg Test (NHPT) [13]. These tests were administered to establish a baseline similar to a recent study investigating the feasibility of a hand exoskeleton [5].

Firstly, in the fitting stage, measurements were taken so that the device was customised to the participant's hand dimensions. After this, the WiGlove and its tablet interface were

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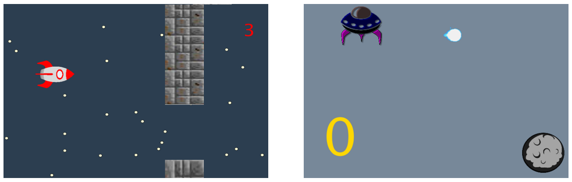

(a) Wrist exercise game (b) Fingers exercise game

Figure 6. Games for training

delivered to the participant's home. During the first week, the participant was encouraged to get familiar with the device by performing flexion/extension exercises and simple activities of daily life like drinking from a bottle and eating with a spoon. Following this familiarisation phase, apart from performing ADL, the participant was introduced to two therapeutic games designed to enhance engagement and motivation for training. These games entailed the user controlling the position of a character and triggering specific actions (e.g., hitting a moving target) by performing flexion/extension of their wrist and fingers (Figure 6).

2) Data Acquisition: During the home-based training period, the tablet logs training data such as joint angle information, number of repetitions, training duration and time, which are later retrieved to analyse and monitor the participant's performance. The participant was also encouraged to complete an online questionnaire about their experience with the device once a week. Furthermore, an in-person semi-structured interview after the first three weeks and at the end of 6-weeks is used to gather his feedback on training with the device. The audio of the responses is recorded, transcribed and analysed. Additionally, similar to [5], The Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0) questionnaire was used to record his level of satisfaction with the WiGlove on a 5-point Likert scale [14]. During this first half of the study, the participant was visited twice to collect the data.

IV. RESULTS

This section presents the results from the formative study with the stroke therapists and the feasibility analysis involving one stroke survivor.

A. Formative evaluation - Stroke therapists

The statistical results of the therapists' feedback are presented in Table I. Overall the participants gave a median score above 4 for most categories while performing a cylindrical task with the WiGlove was judged to be the easiest with a median score of 6.5. Furthermore, the participants unanimously gave high scores for the WiGlove's aesthetic appeal and safety as evidenced by their corresponding interquartile ranges. Among the different grasps, performing the palmar pinch received the lowest median score of 4 indicating a neutral opinion. The following remark by a participant provides insight into the probable cause for this low score.

TABLE I. RESULTS OF THERAPISTS' FEEDBACK (1 - VERY DIFFICULT, 7 - VERY EASY)

	Median	Inter Quartile Range
Ease of donning the forearm module	4.5	1
Ease of donning the hand module	5	0.75
Ease of donning the fingercaps	5	1.5
Ease of doffing the forearm module	5	1.5
Ease of doffing the hand module	5	0.75
Ease of doffing the fingercaps	5	0.75
Ease of performing the ab/adduction of the wrist	4.5	2.5
Ease of performing the ab/adduction of the fingers	3.5	1
Perception of the weight	4.5	2
Ease of performing a palmar pinch (key grasp)	4	1.5
Ease of performing a cylindrical grasp(bottle)	6.5	1.75
Ease of performing a spherical grasp(ball)	5.5	1.75
Suitability for ADL	4	2
Aesthetic appeal	5	0.75
Perception of user safety	5	0.75
Perception of safety for the family	5	0

Therapist 2 - "*I found that the nuts of the glove were resisting my normal movement.*"

1) Design Revisions:

- The palmar pinch requires the thumb and the index finger to flex more than the other grasps. The presence of nuts on the device above the metacarpophalangeal (MCP) joints of the fingers (knuckle) could have restricted their flexion and ab/adduction reflected by its corresponding median score of 3.5. Although. Plastazote foams were used to provide padding from such nuts, the above comment shows that this did not provide adequate isolation. Hence in the revised design, a custom-made foam found in SaeboFlex was used in the WiGlove to provide isolation and ensure comfortable interaction. This foam was used in SPO where no such issues were reported in user trials. This revision was implemented in the WiGlove before the next phase of evaluations.
- Similarly, another participant raised a concern about a pressure point near the wrist due to impingement from the thumb's mechanism. In the revised design, the thumb's passive joint was moved such that it is located proximal to the line of the wrist to ensure that it does not create a pressure point for people with larger hand sizes. Although, given that this was raised by only one participant, this could be due to a mismatch in the glove's size where the thumb's passive mechanism impinges on a participant with a larger wrist. Unlike this study, the device's dimensions will be customised to the stroke survivor's hand in the succeeding stages.

B. Feasibility Study - Stroke Survivors

This manuscript reports the results from the first half of a 6-week home-based training study with the first participant. The participant, using his dominant (unimpaired) hand, was able to move 34 blocks in 60 seconds during the BnB test and complete the NHPT test in 35 seconds. However, when using their impaired (left) hand, the participant was unable to

TABLE II. User Experience Feedback

Usability Aspects	**Comments**
Ease of donning/doffing	Due to substantial tone in the elbow and shoulder, the participant was unable to independently don the device and required the caregiver's help. On the other hand, he was able to doff the finger caps and forearm module without help.
Safety	The participant did not find or experience any safety concerns.
Suitability for the home environment	Due to its small size the participant found it easy to store away from the reach of kids. The wireless operation allowed them to train in different rooms including while lying in their bed. It was deemed very suitable for the home environment.
Learnability	Operating the device was perceived to be straightforward and easy to learn.
Battery	No concerns of battery life were raised. It was charged for 30 minutes every day.
Games	The participant found the games very interesting and was very satisfied with the WiGlove's sensitivity for playing them. "**Felt very happy even when I hit just twice**". He suggested that games involving musical triggers and multiplayer games where other members of the family like the grand kids also can be involved would be even more stimulating. "**The grand kids, yeah, they always want to win, yeah that motivating factor** "
Comfort	It was perceived to be very comfortable
Weight	The participant felt that the device could be lighter. "**It's not heavy, but it could be lighter**"
Feedback on WiGlove's effectiveness	The participant reported observable improvements in his hand with a noticeable reduction in the finger's stiffness. "**It was not supple enough, but over the last two weeks, the mornings, it is very relaxed and soft**", "**How long will, I need, I don't know, but, Definitely, the glove makes a difference**".

grasp any blocks or pegs due to a hyperflexion-induced closed fist. While wearing the WiGlove did enable the participant to grasp boxes they were still unable to complete the test as a result of excessive muscle tone in the shoulder and elbow, impeding gross movements in the arm. Therefore, the baseline for the hand alone was established through an examination of the number of items that the participant was able to grasp, which was 2 blocks in 60 seconds. The participant lacked the necessary range of motion to grasp a peg for the NHPT test. After 3-weeks of training, while wearing the WiGlove, the participant was able to actively pick and drop 9 blocks in 60 seconds compared to the 2 at the beginning of the study. The participant had not yet gained enough RoM to perform NHPT. Both tests will be performed again at the end of the study to evaluate the impact of the intervention.

Based on the data logged in the tablet, the participant performed hand exercises without the therapist's supervision for an average of 50 (± 42) minutes/day with the WiGlove. It also showed that he often split his daily training into multiple sessions with a maximum of 3 sessions on a specific day leading to a total training duration of 175 minutes. Furthermore, the participant's comments during the 25-minute semi-structured interview are summarised in Table II. Based on his experience of using the WiGlove for three weeks, he gave it a rating of 3.75 on the QUEST 2.0 satisfaction scale.

V. Discussion

Overall, the therapists positively rated the ease of donning/doffing the WiGlove independently. Evident in their comments shown below, the therapists believed that hemiparetic stroke survivors would be able to don/doff the WiGlove easily and would only be limited by their cognitive ability. They pointed out the need for written instructions to guide the users during the familiarisation stage.

Therapist 1 - "*Appears suitable for patients to do. However, would be limited to those cognitively able to do so*"

Therapist 3 - "*Would need a good level of cognitive ability. Can be a bit fiddly the first few times*"

With regard to the WiGlove's weight, although the therapists' scores indicate a neutral opinion, this is similar to the median score (4.5) given by healthy participants in the previous study who tried the WiGlove first before trying [11]. In the previous study, the participants who rated the WiGlove after trying SPO overwhelmingly rated the WiGlove to be lighter. Since the therapists only tried the WiGlove, the neutral score could be attributed to a lack of reference for comparison. This will be verified in the study with stroke survivors. This and the ease of performing a palmar pinch could explain the neutral score for the WiGlove's suitability for performing ADL. Given the changes implemented, we anticipate that stroke survivors will not face the above issue faced by therapists and find it easy to perform activities of daily life while wearing the WiGlove.

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Unfortunately, due to the excessive weakness in the proximal joints of the first participant (stroke survivor) who is discussed in this study, he was unable to perform any ADL, precluding the evaluation of the effects of these design upgrades at this stage. However, the participant was still able to use the WiGlove to regularly train for long durations by performing flexion/extension exercises.

Prior to his involvement in this study, his rehabilitation involved 6 weeks of in-patient therapy to the lower limb immediately after the stroke. Since then, the participant has had three one-hour sessions of therapy(one-to-one with a therapist) every week of which only five minutes were dedicated to hand exercises. On the contrary in the first 20 days of the study, the participant performed hand exercises for an average of 50 (± 42) minutes/day with the WiGlove without the therapist's supervision by splitting his training session. The participant's improved performance in the BnB test after 3 weeks could be ascribed to him regaining some active RoM due to this increased training intensity and familiarisation with the device. This serves as promising preliminary evidence for the WiGlove's effectiveness.

The participant's adherence to training could be attributed to the usability of the WiGlove based on their feedback in the semi-structured interview. Overall, the responses indicate a positive experience and acceptance of the device as evidenced by their QUEST 2.0 score of 3.75 which is classified as "more or less satisfied to quite satisfied". Although the games were introduced to him 10 days after the study began, he did not interact with them more than twice, due to unrelated secondary health complications which reduced his overall daily training durations and the use of the WiGlove. This precludes analysis of the effects of the games on the training duration in the first half of the study. This will be studied upon completion of the 6-week study period. However, his feedback based on the initial interaction with the games shows a positive impression and attitude towards training with the games.

VI. Conclusion

The WiGlove is a passive robotic orthosis designed to facilitate home-based rehabilitation of the hand and wrist in stroke survivors. This manuscript highlights the different aspects of the device and reports on its evaluation by six stroke therapists and early evidence from a feasibility trial that has begun with one stroke survivor. The objectives of these evaluations were to assess the WiGlove's usability and its feasibility as a home-based rehabilitation device. Stroke therapists positively rated the usability of the WiGlove and their feedback was used to improve its design. The preliminary results of the study with the one stroke survivor serve as evidence supporting the feasibility of the WiGlove for home-based therapy and reaffirm its usability. Due to the supportive results, a second stroke survivor is now being enrolled with an expectation to recruit up to 4 patients for this feasibility trial.

Future work will involve the continuation of this study with stroke survivors experiencing varying levels of motor function deficits in the hand to validate its feasibility further and evaluate its effectiveness in helping hemiparetic stroke survivors regain their ability to perform activities of daily life.

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