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Us'em: The user-centered design of a device for motivating stroke patients to use their impaired arm-hand in daily life activities

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Abstract—**Stroke leaves the majority of its survivors with an impairment of the upper extremity that affects their ability to live independently and their quality of life. Rehabilitation research shows that practice of everyday life activities in a natural context may sustain or even improve arm-hand performance, even during chronic stages after stroke. Based on this insight we designed, developed and evaluated Us'em; this consists of two watch-like accelerometry devices that provide feedback to stroke patients regarding the usage of their impaired versus their non-affected upper extremity. System usability and treatment credibility/expectancy were evaluated positively by therapists and patients.**

I. Introduction

STROKE, or cerebrovascular accident, is a sudden disruption in the blood supply to brain tissue, leading to a rapidly developing focal neurological disturbance of brain function [1]. Stroke is the leading cause of morbidity worldwide and the first cause of motor handicap [2,3]. Because of the ageing of the population, the incidence of stroke and the health-related costs are expected to rise by 33% in Europe between 2000 and 2025.

Approximately 80% of acute stroke patients suffer from acute hemi paresis [4, 5]. This unilateral motor deficit leads in approximately 40% of stroke patients to chronic upper extremity impairment, limiting functional use as well as engagement in social life [5, 6, 7, 8]. According to Nichols-Larsen et al [9] impaired arm-hand performance is a serious and underestimated problem that is associated with poor quality of life after stroke. By the end of the first year after stroke, approximately 40% of stroke survivors need assistance for activities of daily life [10]. Four years after stroke, 67% of stroke patients still have major problems with non-use or disuse of the affected arm [11].

As it turns out, stroke patients do not reach their full potential when they are discharged from hospital [12], a finding corroborated by studies with chronic stroke patients that have been discharged [13-16]. After discharge there are little therapy and care services available for stroke patients, leading to high levels of patient dissatisfaction [17]. Given the prevalence of stroke, and, in addition, the challenges regarding arm-hand function rehabilitation, the development of technologies to support arm-hand rehabilitation even after discharge, promises great benefits to patients and the health care system.

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II. The Importance of Use for Recovering Function

Taub et al [18] describe the learned-non use phenomenon, which is a 'learned' suppression of movement in the affected arm that is related to the brain damage, but does not itself result from the damage of the nervous system per se. The most direct way to prevent stroke patients from developing learned non-use is to stimulate use of their arm and hand.

Numerous experiments have shown that forced use of the impaired upper extremity in the course of Constraint-Induced Movement Therapy (CIMT) can improve arm-hand performance substantially [19, 20]. During CIMT training, patients are encouraged to perform functional tasks with the impaired arm (5-6 hours a day), while the non-impaired arm is restrained by wearing a mitten (90% of the waking hours). Effects of two-week CIMT sessions can be retained for at least two years after cessation of the training [21].

The CIMT method forces a behavior change regarding the use of the impaired arm-hand. Although effective it is expensive in terms of its demands on therapist time as well as taxing on the patient. The challenge emerges to develop technologies that motivate patients to increase voluntary and unsupervised use of their impaired arm-hand during daily life in all stages after stroke. This can mitigate learned non-use and improve motor learning avoiding the problems related to constraining movement of the non affected extremity.

Usage of the arm-hand in real life situations is of paramount importance. Following the state of the art in stroke rehabilitation, training of arm-hand function ought to be task-oriented [22]; this means that training should be relevant to daily life tasks and preserve their complexity. Task-oriented training approaches have been shown to improve arm-hand performance in everyday life activities [16, 20]; this is in contrast to traditional training approaches at a function level which are limited to providing benefits at this level, e.g., increase range of motion, increase of muscle strength with limited transfer of training effects to real life [22]. In conclusion, the more the impaired arm-hand is used

for skill execution in a natural context, the more patients will learn by solving specific and realistic problems, pertaining to anticipatory locomotor adjustment, cognitive processing, and efficient goal-oriented movement strategies [23].

Following this rationale we designed Us'em, an appliance designed to monitor arm-hand performance during everyday life activities and to give feedback to stroke survivors about the amount of use of the impaired arm-hand in relation to the non affected arm and hand. In the remainder of this paper we discuss the Us'em concept, its design and implementation and its evaluation by patients and therapists.

III. US'EM: CONCEPT OVERVIEW

Us'em is a wearable device that can be described as a persuasive technology [24]: it monitors a patient's behavior in order to provide feedback to motivate using the impaired arm and hand during the course of everyday activities to the fullest possible extent.

The system consists of two parts: a wristband-like activity monitor (Figure 1, left) and a watch-like activity monitoring unit that also offers graphical feedback on a small screen and push-button controls (Figure 1, right). Gebruers et al [25] investigated, in a systematic review, the clinimetric properties of accelerometer-based measurement techniques in persons with stroke. They found that accelerometry yields valid and reliable data about the physical activity of patients with stroke. Uswatte et al also report that patients were compliant with wearing the accelerometers at home [26].

Feedback during training is known to support motor learning for stroke survivors as it compensates for impaired intrinsic feedback mechanisms, such as visual, tactile, proprioceptive, and auditory cues [27]. Feedback is also associated with high training effects [28]. Next to supporting motor learning, feedback can positively influence motivation, self-efficacy, and compliance [29, 30].

Us'em provides feedback to patients regarding the ratio of movement of the impaired arm compared to the healthy arm. The choice of feedback was based on results from studies by de Niet et al [31] and Acuna et al [32]. They showed that in normal persons, the activity levels that are measured with accelerometers are similar for the dominant and non-dominant arm during daily life activities, while in stroke survivors the affected arm shows a significantly lower activity level [31].

Feedback is displayed as a graphical representation of activity on the screen of the watch-like device; this may either provide an overview of the activity ration for the two arms over several days or may describe the arm activity ration pertinent to one specific bilateral activity, such as eating a meal. Monitoring arm-use during a specific activity requires starting and stopping the measurement, in a stop-watch like fashion at the start and end of that activity.

IV. ITERATIVE USER CENTERED DESIGN OF US'EM

A user-centered design process was followed [33] involving patients, therapists, rehabilitation researchers, and interaction design experts. The device has been designed and developed in four iterations, where different aspects of the functionality and form have been addressed. We discuss these in detail below.

Fig. 1 The Us'em system consisting of a wristband device with accelerometer and communication modules and a watch-like device equipped with a graphical display as well (right).

A. Iteration 1

Interviews and focus groups were held where various scenaria for motivating use of the arm-hand through technology were evaluated by therapists, patients and their close family. The following requirements were thus identified: a) Monitoring and feedback should focus on daily activities carried out in a natural environment in the rehabilitation centre or at home. b) The system should monitor patients in a minimally obtrusive manner and fit into their daily activities. c) The system should provide meaningful feedback to the patient about the use of the impaired arm-hand both in general everyday life, but also related to specific arm-hand skills. d) The patient should be able to use the system independently

A tethered proof of concept prototype of the feedback mechanism was implemented using Phidgets (http://www.phidgets.com). Phidgets are a technology suitable for the fast prototyping of sensor based applications [34]. The software was written in Max MSP, a data flow oriented programming language for rapid prototyping of multimodal applications. The prototype (that did not show any indication as to the final form of the device) was accompanied by a 'training card' system for assisting patients in setting their training-targets.

This prototype was evaluated in focus group sessions with therapists (N=3) and patients in the sub-acute stage after stroke (N=4). From these sessions it became clear that the training/motivation cards are unnecessary: patients do not need to be convinced to train and practice; rather, they lack

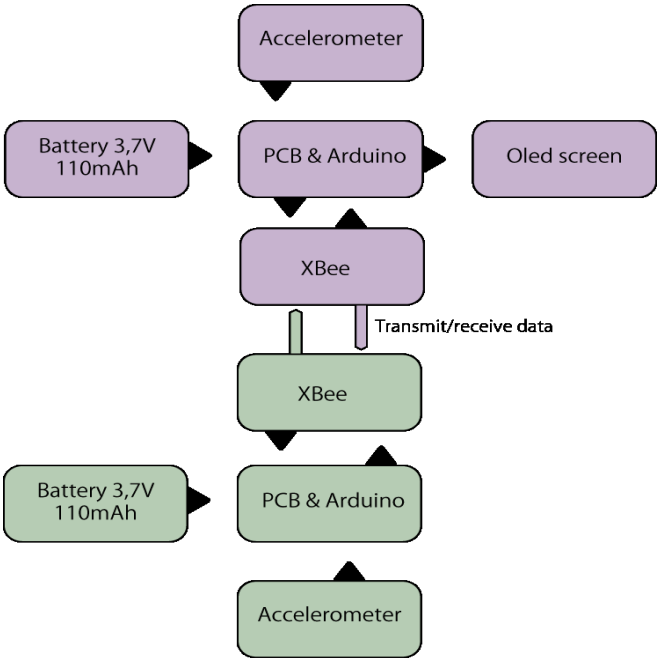

Fig. 2. Hardware configuration of Us'em

knowledge as awareness about their progress without technology aids. They can only notice progress after weeks of training, so the value they expected from Us'em would be to provide finer grain information regarding their efforts and progress.

B. *Iteration 2*

In a second iteration un-tethered wrist-worn devices were built housing wireless sensors; the sensors communicate wireless with a PC through the ZigBee protocol; the MaxMSP application was improved to provide feedback on the relative movement of the devices. The electronics were cased in a 3D printed prototype of the devices worn by patients (see the device with the display in fig.5). The prototype was demonstrated to therapists (N=4) and patients (N=7, of which 3 were in the sub-acute phase and 4 in the chronic phase after stroke).

Varied feedback was obtained regarding the ergonomics and material aspects of the device: they expressed their need for a smaller more discrete and comfortable device, easier to use buttons and straps they can put on and off unaided; they expressed doubts whether they could wear it for whole days.

Patients found the device most suited for the start of the sub-acute phase or straight after stroke when they are mostly dealing with (re)learning to use their impaired arm and hand. They thought it would be less useful for later phases where many have found ways to compensate for their disability. Therapists on the contrary considered the device also useful for preventing learned non-use for chronic patients, as it may support to maintain the training effects that were achieved during the rehabilitation, preventing that the patients would fall back into a negative spiral of disuse. They thought the device may even support patients to improve further through sustained use of the arm hand in more (and more difficult) tasks. Therapists suggested that patients should be introduced gradually to this device when still receiving regular therapy sessions; patients need to learn how to interpret the information presented to them. Therapists also saw potential about using the device during supervised training; they had concerns regarding how long its persuasive impact might be sustained for and wished for the validity of its measurement to be established.

C. *Iteration 3*

In this third phase, the software was ported to the embedded microprocessors allowing for the independent operation of the device, i.e. away from any computer. The interaction was kept roughly the same as in iteration 2.

1) *Hardware*

Accelerometers (Breakout ADXL335) are embedded in both devices, while only the device intended for the most affected arm is equipped with an OLED display (4D Systems UOLED-96-G) Accelerometer data is read by an embedded Arduino (Pro Mini 3.3.V) board. Communication between the devices is supported by Xbee wireless data transfer modules. The software written in C# was implemented on the embedded Arduino processors.

The hardware design of Us'em is shown in Figure 2. The two modules are similar in hardware design except for the additional buttons and OLED-display on the feedback module. A rechargeable battery system (Polymer Lithium Ion Battery, 3.7V, 110 mAh) provides power to the different components. USB connectors have been integrated in the units to recharge the internal batteries. Tactile switches integrated in the sides of the rapid prototyped casing enable user input. To achieve a wearable, minimally intrusive solution, components were selected based on having a small footprint and minimal weight.

2) *Interaction & Interface*

The system offers three modes of operation which can be selected by using buttons on the feedback module (see figure 3). In the default "clock" mode the device acts as a watch displaying the time. In the "overview" mode, the system provides feedback about impaired arm-hand use ratio in the

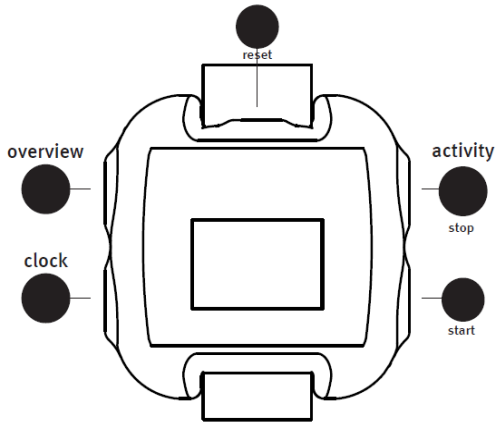

Fig. 3. Push-buttons on the device and their purpose

Fig. 4: Feeback of use ratio: (a) comparison to previous 6 days and (b) stopwatch function for one activity.

last few days. This data is monitored and stored continuously, independent of the mode of operation. In the "activity" mode, the patient can use the module to monitor arm-hand use during a specific activity by starting and stopping the measurement as with a stopwatch.

The feedback module containing the display and buttons is worn on the affected arm. This ensures that the user is able to press the buttons using the non affected arm. Furthermore, the patients' attention is drawn towards the affected arm and hand inherently by wearing the device there.

3) Feedback design

Us'em monitors the daily use ratio of the patient's arms. The feedback module communicates the use ratios during the current day and compares it to the ratios of the last six days; this communication and display function is triggered when the user presses the overview button.

The ratios are represented by a bar graph. A yellow reference line displays the ideal use ratio (see figure 4a). The bar graph consists out of several rectangles of which the height variable is similar to the use ratio of that particular day divided by a specific factor that ensures that the rectangles fit on the display. The leftmost rectangle represents the use ratio of the present day and can be colored green or orange. The color of the bar depends on whether the ratio increased (green) or decreased (orange) with respect to the use ratio of the previous day. The comparison between the present use ratio and the use ratio of the previous day is underpinned by simple textual feedback.

The third functionality of the prototype is monitoring specific activities. This functionality allows the user to start and stop monitoring a specific activity. The monitored movement is translated into a score that is rendered in real-time on the display of the feedback module. The display also provides information of the previous measurement so that users can quickly compare their current score to the previous one. When pressing the stop-button stops the measurement, an overview of the last seven measurements is displayed represented by a bar graph (figure 4b). This graph does not show a reference line since the monitored exercises may change from time to time.

D. Iteration 4

This final iteration was aimed at reducing the size of the devices, increasing their robustness, and facilitating reproduction in larger volumes for larger scale experimental deployment. The final device is as shown in fig.1. Electronics are now implemented on printed layout boards, power management has been implemented, and casing is now molded rather than 3D printed, allowing for cheaper and faster manufacturing and more robustness. The size of the device for the damaged arm is (h=18mm, w=40 mm, l=50mm) and (14, 40, 50) for the less damaged arm, achieving a substantial reduction (between 10-20% on each dimension compared to the prototypes of iteration 2 and 3).

The battery life in the current prototype is over 4 hours; clearly, longer operation times are required for use in therapy, which is the target of on-going work.

V. USER EVALUATION

A. Method

After iteration 3, a user test was set up and administered in order to evaluate the usability of Us'em and to measure the credibility and expectancy pertaining to Us'em as a therapy tool. The evaluation plan was approved by the medical ethics committee of SRL, Hoensbroek (NL).

A total of 9 patients, 6 in the chronic stage and 3 in the sub-acute phase after stroke participated in the evaluation. All patients were receiving rehabilitation therapy at the clinic where the tests took place. Patients were selected by therapists ensuring that while they suffered from arm-hand function impairment, they did not suffer from cognitive impairment, and they could understand and participate in the test.

Participants were greeted, received a brief verbal introduction and orientation to the test, and then carried out a series of tasks relating to the functionality of the device: e.g., reset it, perform a familiar exercise with the therapist, check feedback for two arms, perform exercise alone, enter and exit different operation modes. Participants were given a small card/manual with explanations regarding the purpose of the buttons.

Therapists and patients were asked to rate the products using the CEQ inventory [35] for measuring credibility and expectations from the device as an instrument for therapy; the scores on this scale can range from 9 to 27.

Fig. 5. The earlier version of the prototype used in the usability and credibility test.

B. Results

1) Usability

All participants reported that the size of the modules was too large (they tested the prototypes of version 3). However, all participants mentioned that they wouldn't feel ashamed wearing the modules despite their sizes. The attention that the modules could draw was considered in different ways. Most representative, is that of a female participant who stated that she wouldn't wear Us'em to a party because she wanted to look elegant and didn't want to have to explain her story over and over again when people would ask about the devices. On the contrary, one male patient explained that he would like to wear the devices among family and friends. In his case, the modules could provide a conversation topic and he would enjoy explaining to everybody how they work and what he does with them. In both cases, miniaturization was found necessary, motivating the efforts of iteration 4.

The small size of the display was not considered a problem for the majority of the participants. Just one participant, who had forgotten his reading glasses, had trouble with reading the textual information, though he could grasp the nature of the information by looking at the graphs only.

The performance test proved that the buttons were one of the main limitations of this device. First of all, the layout of the buttons proved hard to learn for most of the participants. Of course, the short duration of the test did not allow them to master the prototypes, as one would in real life use. There was a clear distinction between the participants in the age-range of 41-50yrs and the older participants. The youngest participant performed all tasks quickly and without errors regarding button choice even without consulting the manual/card provided.

Participants complained regarding push buttons (note that they were using the prototype of iterations 2 and 3); these were concealed under the printed casing, so were not visible and they were difficult to press because of their arrangement (see figure 5). These problems have been improved in the final version of the prototype shown in figure 1.

2) Credibility and Expectancy

A neutral score on the CEQ equals 15. Patients' credibility scores ranged from 20 to 25.5 (mean=22.6, SD=2.01), indicating that they found the Us'em system credible for treating their arm hand symptoms. Treatment expectancy scores ranged from 4.08 to 23.4 with an average score of 17.36 (SD=6.02). On average, patients expect their arm-hand performance to improve by using Us'em. A trend was seen for credibility scores to be higher in chronic stroke patients and expectancy scores to be higher in sub acute stroke patients.

VI. Conclusion

Us'em is an appliance designed to motivate stroke patients towards increasing the use of their impaired arm and hand in everyday life activities in their own living environment. Motivating feedback on the amount of use of the impaired arm and hand is given to patients. Progress over time can be assessed by the patient for overall activity as well as for specific arm-hand skills. This paper described the iterative design of this device and a user test conducted with patients. Treatment credibility and expectancy was rated to be good by both sub acute and chronic stroke patients.

Current research aims to extend the autonomy of the devices, allowing for longer term field deployments. This will allow more confidence regarding the subjective experiences and attitudes reported by patients and therapists, and will also allow to evaluate the impact of this device upon patient behavior.

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