The development and evaluation of an arm usage coach for Stroke survivors

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Abstract—**Physicians currently have no objective information about the intensity and quality of a Stroke patient's daily-life activities after returning home from the rehabilitation hospital. Therefore there is a need to unobtrusively monitor patients performing daily life tasks at home. Within the INTERACTION project, a new inertial based sensor suit was developed, which is able to measure Stroke patients at home. This research extend the INTERACTION project by developing an Arm Usage Coach (AUC), which stimulates the patients affected arm to be used more often at home. The results of a usability evaluation showed high scores in usability, but some design and wear ability problems were found. An open loop evaluation of Stroke patient data showed how different decision criteria parameters, for applying feedback to the patient, resulted in different outcomes of feedback given. Based on both evaluation results, a new prototype is in development, which will be evaluated by Stroke patients in clinic.**

Keywords-component; vibrotactile feedback; inertial sensing; stroke; usability

I. INTRODUCTION

The changes in functional capacity and performance of stroke patients after returning home from a rehabilitation hospital is unknown to a physician. They have no objective information about the intensity and quality of a patient's daily-life activities. Capacity describes what a patient is able to do, this can be measured with clinical tests like the Fugl-Meyer test [1] in a standardized clinical environment. Performance describes what a patient is doing in actual practice (for example, during daily life, at home). Therefore, there is a need for an unobtrusive and modular system for objectively monitoring the stroke patient's upper and lower extremity motor function in daily-life activities. In the INTERACTION project, a sensor system was developed, based on inertial, strain, goniometer, pressure and EMG sensors, for monitoring Stroke patients during daily life activities [2].

Results of earlier studies showed that capacity measurements in clinic do not automatically transfer to the performance of a patient during daily life situations [3], [4]. From the first results of stroke patient measurements, we observed differences over time in arm usages between the affected and non-affected side. In some patients we saw more use of the non-affected arm at home, which eventually could lead to a loss in affected arm function over time. Possible causes could be a missing motivational factor at home, functional need of the arm (ease of use), that the patient feels unsafe in an uncontrolled environment and neglect. Hence, there is a need to assist stroke patients during daily life situations to motivate, or remember them to use his/her affected arm more often.

This can be done by providing vibrotactile feedback (VT) to patients to stimulate the usage of their arm. Other modalities such as visual, auditory or haptic feedback (in multimodal systems) are mostly used in training systems, focusing on capacity, and are to obtrusive within a social context in a home situation. In order to transfer the patient's capacity to daily life situation, this should be minimized [5] [6]. Providing vibrotactile feedback to patients have been studied, but no research has been done on a realisation of a system that actually provides feedback during daily life [7,8, 9, 10, 11, 12, 13] .

This research aims to extend the INTERACTION system to not only monitor and analyse the movement data, but also making a decision whether to give feedback to the patient or not, i.e. the *decision* component, and how the *patient* can be stimulated to move the paretic arm more, i.e. the e*ffectuate* component. In this paper, we present an "Arm Usage Coach" (AUC) that can be used in daily life situations by Stroke patients. The UAC will target sufficient arm movement quantity, rather than quality of arm movement and utilizes inertial sensors and vibrotactile feedback for providing patient feedback. Section II includes a summary of the requirement analysis which has been done as part of system development. In section III the algorithms will be explained and in section IV, the final prototype will be presented. User and technical evaluation are described in sections V and VI. The discussion and conclusion are presented in sections VII and VIII.

II. REQUIREMENT ANALYSIS

First, a Function Analysis System Technique (FAST) [14] was used to formulate the functional requirements the system must have. From this analysis the following function were identified:

1. *Stimulate affected-arm-usage* is the main function of the system. There is need to *stimulate* the *patient* to use his/her affected arm during daily life, which is based on monitoring the patient's arm movement and to decide whether to give feedback or not.
2. Awareness can be created by *providing feedback on arm movement* to the patient which can be done by

3. *Monitoring* the movements of the left and right arm of the *patient* to *make* a *decision* whether to provide a stimulus or not.
4. The final step is to *provide* the *stimulus* itself.

Interviews have taken place with therapists and vibrotactile experts at Roessingh Research and Development B.V. and the University of Twente respectively. From these interviews, non-functional requirement have been determined, which are described below.

1. *Placement of sensors*
   Placing tactors on hairy skin, in locations where bone comes closest to the skin and outside joints or areas of movement of use is advisable. When placing multiple tactors it is essential to ensure that the distance between tactors is at least the 2-point discrimination threshold, which varies over the body, in order to recognize the distinction between tactors [4]. The tactor is placed either on the affected or the non-affected side, depending on the ability of the patient to feel a sensation on the affected side
2. *Timing of feedback*
   Timing of the feedback is an important aspect. During an interview with a Stroke rehabilitation expert, it became evident that feedback is least effective during movement, while providing feedback directly after the movement is significantly more effective. Both types of feedback are called ‘knowledge of performance’. Feedback provided after a certain period is most effective, this type of providing feedback is called ‘knowledge of result’. Due to the fact that some patients also suffer from cognitive impairments, only providing knowledge of result is not desirable. It is therefore suggested to use a combination of knowledge of performance after movement and knowledge of result.

III. ARM USAGE COACH ALGORITHM

For tracking arm movements, two Xsens MTw inertial sensors were used. This solution allows to synchronize multiple Mtw's with each other. The Xsens Awinda protocol ensures real-time sending and receiving of data and handles data packet loss [15].

A. Metric

In order to detect movement of the arm by using 3D accelerometers, a certain metric has to be defined. We created a new metric called the Difference Acceleration Vector (DAV). The length of the DAV is calculated by subtracting a reference gravitational acceleration vector **g(t)** from the current acceleration vector **a(t)** and taking the norm of the resulting vector. The length of the DAV, called "d(t)" is defined as follows:

$$d(t) = \sqrt{\left(a_x(t) - g_{x,t0}\right)^2 + \left(a_y(t) - g_{y,t0}\right)^2 + \left(a_z(t) - g_{z,t0}\right)^2} \quad (1)$$

Finally, the mean DAV is calculated over a time period T_{dav} of measurement data, which by default is one second. Figure 1 shows a graphical representation of how the DAV is calculated. With each dashed arrow, there is a switch between the global and sensor frame. In Figure 1 the reference acceleration vector, shown in Figure 1B, is subtracted from the acceleration vector at a current time point, shown in Figure 1A. Figure 1C is the result of combining A and B. After the subtraction, the length of the difference acceleration vector can be constructed from the components, shown in Figure 1D.

The DAV metric has been evaluated by measuring daily life movements in health subjects which performed movements like walking, reaching and simulating Stroke patient movements. Clear distinctions in the DAV were found among the different movements and therefore this metric was chosen as a measure for arm usage. [16]

B. Decision making

The decision criteria are based on three input parameters: 1) a threshold value “Th_{arm}” for the DAV, 2) amount of desired affected arm movement as a ratio, called desired ratio “R_{arm}” and 3) time period “T_{adl}” . Raw acceleration data of both sensors is processed to calculate the length of the DAV, d(t), by subtracting reference data which is obtained from a short calibration before each measurement. Next, the amount of samples is counted within a certain time period T_{adl},, where the DAV is above the threshold value. This is done for both the left and right arm and a ratio between the two counters is determined. If this ratio is smaller than “R_{arm}”, feedback will be given. The default value for threshold “Th_{arm}” to detect activity is 5 m/s^2, as walking tends to generate values that range between 2 and 4 m/s^2. The desired ratio is determined by a therapist. A desired ratio “R_{arm}” of 0.2 means that after five non-affected arm movements, one affected arm movement has to be performed. A flowchart of the Arm usage coach algorithm is shown in figure 2.

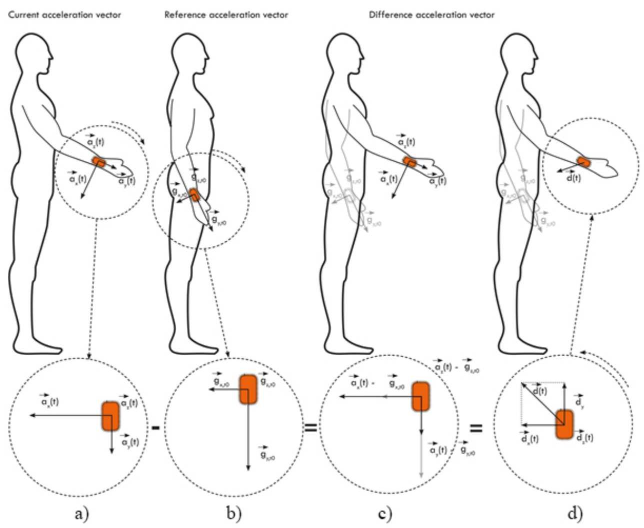

Figure 1: Calculating the DAV

IV. PROTOTYPE IMPLEMENTATION

The prototype is shown in figure 3. Two Xsens MTw´s are connected wirelessly via an Xsens dongle to a laptop running Matlab [17]. An Elitac vibrotactile system is chosen for giving feedback to the patient, because it is easy to control via Matlab and it is already available on the market [18]. Both intensity and frequency pattern of feedback can be adjusted in the Elitac system and together with the final actuation of the tactor are called “Feedback processes”. The Elitac system is connected via Bluetooth to the laptop. For development purposes, two algorithms were developed in Matlab: a data acquisition script and a data translation and feedback script. Each is running on a separate Matlab engine. The data acquisition script, used in previous research [2], is customized in order to ensure real-time data streaming from the Xsens sensors to Matlab where triaxial (x, y, z) accelerometer data with corresponding time stamps is logged in a circular buffer with a frequency of 20Hz. This circular buffer is used to split up the data acquisition process from the data translation and feedback processes. At first, the previously mentioned decision criteria must be entered within the algorithms main user interface. For obtaining the reference acceleration vector, a calibration neutral n-pose (standing straight with hands alongside the body, feet pointed forward and shoulder width apart) is needed. This vector is acquired during the first 10 seconds of measurement.

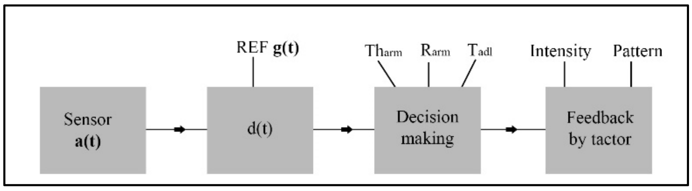

Figure 2 Flowchart of the AUC

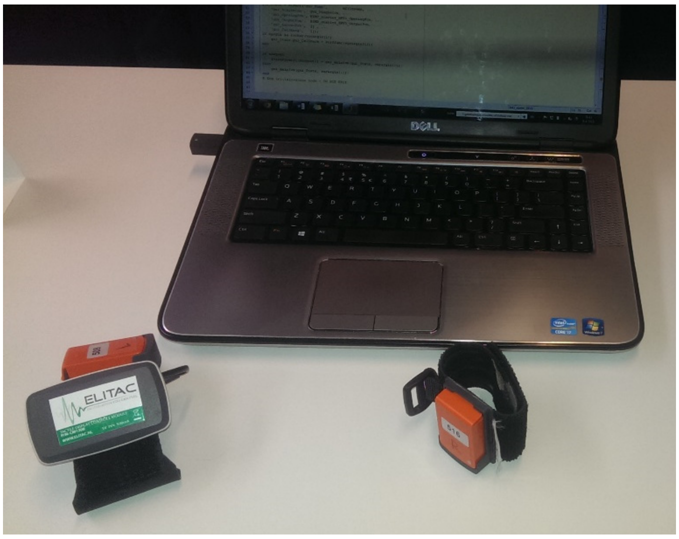

Figure 3 AUC prototype. In the picture, two Xsens MTw (orange boxes) and one Elitac module are shown.

V. USABILITY EVALUATION

A. Methodology

Five healthy subjects, who have knowledge about Cerebrovascular accidents, have been included as part of this study. Subjects were asked to put on the wristband with sensors on each arm. The data acquisition algorithms in Matlab was started on a laptop and a connection with the Xsens MTw and Elitac system was established. After the connection was made, the subject was asked to stand in n-pose for 10 seconds. Next, the data translation and feedback scripts were started on a second Matlab engine. The default set of parameters implemented in Matlab (Th_{arm} =5, R_{arm} =1) is used for each subject. Subjects were asked to perform a specific set of combined tasks that represents daily life activities. The complete protocol has been described in [19]. This specific set of tasks are as follows: 1) Sit behind a desk. 2) Stand up and walk to the door. 3) Open the door, walk through it and close it again. 4) Walk to the table. 5) Move object. 6) Pick up object 2. 7) Walk back to the door and open it. 8) Walk through the door and close it again. 9) Take a seat behind the desk.

This set was performed twice per subject, one time while performing as a healthy subject, one time simulating a stroke patient with a left affected side. After both sets of combined tasks were performed, the subject was asked to fill in the System Usability Scale (SUS) [20], the Computer System Usability Questionnaire (CSUQ), [21] and a short interview was taken to ask about the opinion of the participants.

B. Results

The answers from the SUS and CSUQ were analysed and mean and standard deviation were calculated for both questionnaires. These are listed in table 1 and 2 respectively. According to the subjects, the wristband was not comfortable to wear, the system is large and oversized and the system did not consider different types of movement. However, the vibration is not annoying or obstructive, the system is not harmful and it is easy to learn how to use the system. Finally, according to the subjects, the system had a stimulating effect on the awareness of using the arm more often when simulating a Stroke patients.

TABLE I: SuS results

Score of SuS	*Mean*	*Std*
Overall	75.0	7.2

TABLE II: QSUS results

Score Name of CSUQ	*Mean*	*Std*
Overall	5.5	0.8
System use	5.9	0.8
Information quality	5.8	0.2
Interface quality	5.6	0.6

VI. OPEN LOOP EVALUATION

A. Methodology

Besides a user oriented evaluation, we want to know to what extend the decision criteria input parameters influence the vibrotactile feedback rate and how the system would perform in daily life stroke patients. Within the INTERACTION project, large amount of Stroke patient data was captured with a full body inertial measurement suit. As the data acquisition script was separated from the data translation and feedback scripts, it made it possible to process earlier captured movement data. However, this is an open-loop situation as the patient doesn't get feedback and therefore cannot adapt, but it should give a good insight as to how the decision criteria input parameters influence the feedback repetitions given. For this evaluation, a seven minute measurement session was taken which includes many short daily activities around the house (sitting, standing, walking, grabbing objects, and doing dishes). INTERACTION includes an activity recognition algorithm and the output is shown in figure 4a. The activity recognition algorithm detects sitting, standing, cyclic walking (defines as walking three steps in the same direction), variable walking (steps in all directions) and arm usage. Four different combinations of Tr_{arm} and R_{arm} were chosen and the VT feedback with these settings was investigated.

Results

The results are shown in figure 4. The activity monitor shows a variety of different movements, namely standing with arms in rest, standing with using the arms (can be doing the dishes), walking around the house with variable steps and using the arms (carrying objects) and walking longer distances in a straight line. The patient also sits for a few minutes and uses his arms. The tactile activation are plotted in figure 4b, c, d and e, where each subplot is generated by different decision criteria input parameters.

There are three key points in the timeline (highlighted in green) where each of the settings gave vibrotactile feedback. The activity monitor shows that this is a period of more non-affected arm usage then affected arm. In figure 2b, a low threshold of 3.5 with a ratio of 1 seems to activate the tactor several times after each other, where a slight increase of the threshold greatly reduces the number of activations as shown in figure 4d. Increasing the threshold from 5 to 8 doesn't influence the amount of activations a lot. Decreasing the ratio from 1 to 0.5 as seen in figure 4d and 4e respectively, reduces the number of feedback given.

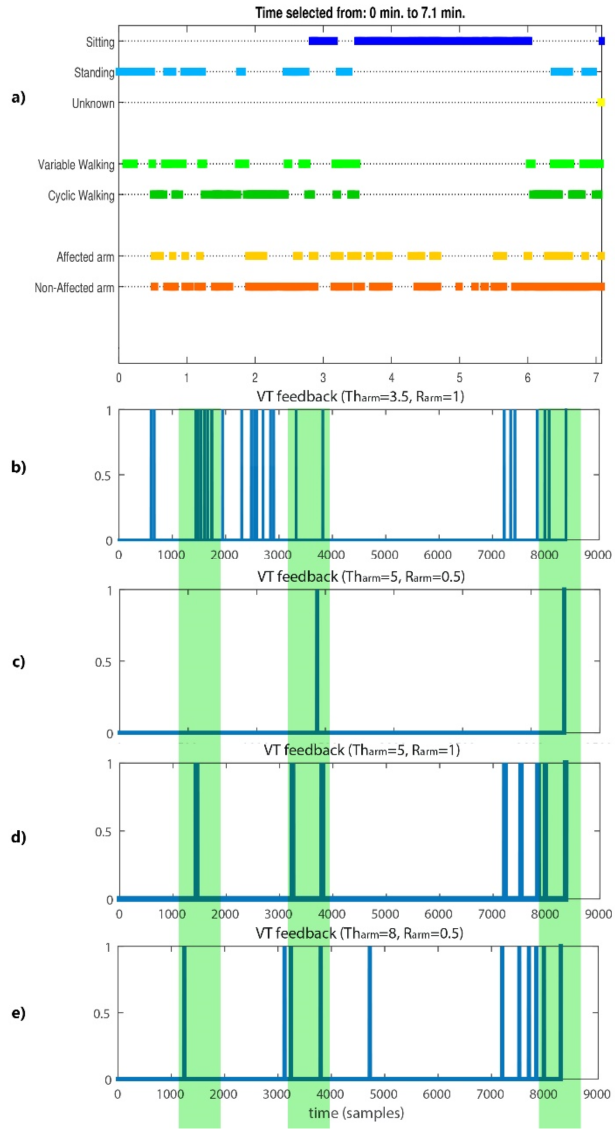

Figure 4: Results of the open-loop evaluation.
4a) Activity monitor results.
4b) vibrotactile results (1=activated,0=not) with Tharm=3.5 and Rarm=1.
4c) vibrotactile results (1=activated,0=not) with Tharm=5 and Rarm=0.5.
4d) vibrotactile results (1=activated,0=not) with Tharm=5 and Rarm=1.
4e) vibrotactile results (1=activated,0=not) with Tharm=8 and Rarm=0.5.

VII. DISCUSSION

The results from the SUS and QSUQ questionnaires showed high scores in usability. The system is safe and easy to use, the vibrotactile (VT) feedback provided was felt and easy to interpret according to the included healthy subjects.

A default set of decision criteria input were used during the usability evaluation. People differ in mobility and their own interpretation of how a Stroke patient handles ADL tasks. Therefore, results could be influenced while the system was not personally configured. A protocol for determining those input parameters should be developed, ideally in an automatic way.

The open loop evaluation shows that the algorithms were able to process Stroke patient data, captured at home. By changing the decision criteria input parameters, the (simulated) vibrotactile feedback could be visualized over time. This, however, was an open-loop situation as the patient was not able to respond and thereby change his or her behaviour. The results showed large differences in VT feedback with different input parameter. By inspecting figure 2, a Th_{arm}=5 and R_{arm}=0.5 seems to be a plausible setting specifically for this patient, with two feedback moments within seven minutes, as frequency and predictability are two important factors in giving feedback [22].

To make a good assumption about optimal settings for Stroke patients, we need to do actual patient measurements. However, what can be seen is that by only using two input parameters, the system can be influenced in such a way that the amount of feedback can be changed significantly. It therefore seems promising to start clinical measurements with setting mentioned earlier. Simulating the VT feedback in this way could be the starting point for automatic determination of the optimal decision criteria input parameters, to make the input parameters patient specific.

In the current prototype, a laptop is used to process data. When building a system for stroke patients to use in an ambulatory setting, it has to be self-supportive and completely wearable. Therefore there is a need to prototype a new system, which should, according to the user evaluation results, be easier to wear and self-supporting at home without the need of a clinician.

VIII. CONCLUSION

The main goal of this research was to "*develop and evaluate an on-body vibrotactile feedback system for stroke survivors to stimulate the use of the affected arm during daily life.*

In this paper a system was developed and evaluated to coach Stroke patients at home in using their affected arm more often. The system was evaluated on healthy subjects and on offline data of Stroke patients in daily life situations. Future research must conclude whether the system stimulates stoke patients to use their affected arm during daily life.

Most of the decision criteria input parameters of the system must be patient specific, i.e. the 'desired ratio', the location at which sensations can be experienced in the affected and/or non-affected side and feedback preference. An early prototype of the proposed system is composed of two Xsens MTw sensors, which were placed on the wrists to track arm movements. A difference acceleration vector (DAV) was calculated for both arms. Feedback is given via an Elitac vibrotactile actuator. A user evaluation protocol was set up to test the system on five healthy subjects and assess the systems usability for future development. They have rated the system with a score of 75.0 (±7.2) at the System Usability Scale and mean of 5.5 (±0.8) for the overall system at the Computer System Usability Questionnaire. The first impression by the participants of the prototype is promising.

In the usability evaluation, subjects noted that the prototype is large and oversized, and that it does not distinguish different types of movement. However, they also noted that one can easily learn how to use the prototype, that it creates awareness on arm movement and that it has a stimulating effect.

An open loop evaluation was done by using accelerometer data of arm movements during daily life activities of Stroke patients. The results show that the algorithms were able to process Stroke patient data and how different decision criteria input parameters resulted in different activation times of the tactor. Interestingly, in this particular dataset, different settings had three key time points in common where feedback was given.

Based on the results of the usability evaluation, a new prototype of the system is currently in development. It includes smaller accelerometers, smaller tactors and batteries that last longer than the current ones, all integrated in an appealing wristband by utilizing 3D printing technology and the Bitalino platform [23]. Instead of a laptop, a small tablet will be used for testing. These steps also reduce the costs of the system significantly. Evaluations with Stroke patients in clinic are planned for the end of 2015. We would like to measure them in clinic for two weeks daily and take baseline measurements before and resulting measurements the week after this intervention. We aim to help Stroke patients in using their affected arm more often during ADL tasks and that this eventually leads to a larger increase in their arm function and better performance at home.

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