A Wearable Bracelet Device for Promoting Arm Use in Stroke Patients

Conference Paper · November 2015

DOI: 10.5220/0005662300240031

5 authors, including:

Belén Rubio Ballester
IBEC Institute for Bioengineering of Catalonia

Esther Duarte
Consorci MAR Parc de Salut de Barcelona

Armin Duff
University Pompeu Fabra

Paul F.M.J. Verschure
Catalan Institution for Research and Advanced Studies - Univeristat Pompeu Fabra

A Wearable Bracelet Device for Promoting Arm Use in Stroke Patients

Belén Rubio Ballester[1], Alica Lathe[1], Esther Duarte[2], Armin Duff[1] and Paul F. M. J. Verschure[1,3]
[1]*Laboratory of Synthetic Perceptive, Emotive, and Cognitive Systems (SPECS), Departament de Tecnologies de la Informacióі la Comunicació(DTIC), Universitat Pompeu Fabra, Roc Boronat, 138 08018 Barcelona, Spain*
[2]*Servei de Medicina Física I Rehabilitació, Hospitals del Mar I l'Esperança, Institut Hospital del Mar d'Investigacions Mèdiques, Barcelona, Spain*
[3]*Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain*

Keywords: Stroke, Learned Non-use, Wearables, Motor Rehabilitation, Hemiparesis.

Abstract: After stroke, many patients experience hemiparesis or weakness on one side of the body. In order to compensate for this lack of motor function, they tend to overuse their non-affected limb. This so called learned non-use may be one of the most relevant contributors to functional loss after post-stroke hospital discharge. We hypothesize that frequent exposure to movement related feedback through a wearable bracelet device may 1) increase the patient's intrinsic motivation for using the paretic limb, and 2) counteract learned non-use, therefore inducing motor recovery. First, to validate the accelerometers-based measurement of arm use, we recruited 10 right-handed volunteers without neurological impairments. Second, we explored the acceptability and clinical impact of a low-cost wearable system on 4 chronic stroke patients with hemiparesis. Our results suggest that frequent exposure to direct feedback about arm use promotes the integration of the paretic limb in the performance of instrumental activities of daily living (iADLs). In addition, results from questionnaires revealed that the use of wearable devices may influence positively the patient's intrinsic motivation for using the affected arm. To the best of our knowledge, this is the first study suggesting the benefits of wearable-based feedback as an intervention tool for counteracting learned non-use.

1 INTRODUCTION

After hospital discharge, up to 55% to 75% of stroke patients experience persistent motor impairments (Lai et al., 2002) and may even suffer substantial declines in function in the following 6 months. A number of studies suggest that this loss may be due to the lack of use of the paretic limb (Lai et al., 2002), a phenomenon that has been called learned non-use. Recent work on studying the dynamics of motor recovery after stroke have shown that learned non-use may emerge as a consequence of decision making for motor optimization, therefore being dependent on two main factors: the expected success and the expected cost of using either effector (Hidaka et al., 2012; Han et al., 2008; Ballester et al., 2015a). On these basis, there may exist different strategies for counteracting learned non-use. For instance, Constrained-Induced Movement Therapy (CIMT) proposes to reduce the probability of success and increases the cost of using the non-affected limb by restricting its movement and tactile feedback using a mitt (Taub and Uswatte, 2003). Recently, we have shown that Reinforcement-Induced Movement Therapies (RIMT) may be complementary to CIMT (Ballester et al., 2015a; Ballester et al., 2015b). In RIMT, visual manipulations during training increase the probability of success and reduce the cost of using the paretic limb. However, these rehabilitation protocols are usually limited to short sessions of intervention and may not be suitable for unsupervised domiciliary environments. In light of these limitations, the use of wearable devices could be specially suitable for the persistent monitoring and treatment of leaned non-use.

The current state of research and technological development shows a tendency towards the gamification of rehabilitation tools, combining various types of sensors to capture motion and posture. Several studies have tested the reliability and validity of using accelerometers for measuring arm use in activities of daily living (Noorkõiv et al., 2014; Uswatte et al., 2005). In this vein, significant effort has been made in evaluating the acceptability of wearable devices that incorporate accelerometers for the quantification of motor performance and recovery (Wang et al., 2014). The application of wearable devices to the rehabilita-

Ballester, B., Lathe, A., Duarte, E., Duff, A. and Verschure, P..
A Wearable Bracelet Device for Promoting Arm Use in Stroke Patients.
In *Proceedings of the 3rd International Congress on Neurotechnology, Electronics and Informatics (NEUROTECHNIX 2015)*, pages 24-31
ISBN: 978-989-758-161-8

tion field offers a number of advantages, such as improved objectivity, sensitivity, and ease of measurement of therapy outcomes. However, because of their ubiquity, wearable devices may be also useful as intervention tools. Their design and interface enables the frequent delivery of multimodal feedback during the performance of iADLs, which may facilitate the realignment of attention towards the affected limb, thus encouraging the selection of the weaker arm.

Recently, Markopoulos et. al (Markopoulos et al., 2011) developed a credibility and usability study on an experimental wearable device that monitors the patient's behavior and displays feedback about the use of the affected versus unaffected arm. So far, previous work on wearable devices for rehabilitation describe prototypes and techniques for the integration of monitoring hardware in wearable garments as well as communications systems (Uswatte et al., 2005). Uswatte et al. conducted a clinical experiment in which 20 stroke patients wore an accelerometer on each arm, the chest, and the more affected leg. Recordings from each sensor were used to estimate the duration of movement as a percentage of the total recording period. Results revealed a strong correlation between the accelerometers-derived measurements and the Motor Activity Log (Uswatte et al., 2006). More recent studies have validated and extended these findings showing strong correlations between triaxial accelerometry-derived measurements and the Quality of Movement scores (van der Pas et al., 2011) or the National Institutes of Health Stroke Scale (NIHSS) (Gubbi et al., 2013). However, there is no evidence yet about the clinical impact of these types of devices.

The aim of this study is to evaluate the potential of a wearable system for measuring the amount of use of the paretic arm in iADLs in chronic stroke patients with upper extremity hemiparesis. Specifically, we hypothesize that frequent exposure to movement related feedback through a wearable device may 1) counteract learned non-use, and 2) increase the patient's intrinsic motivation for using the paretic limb. This work presents results from a pilot study exploring stroke patients' acceptance of a wearable device for independent usage in their home setting and its effectiveness as an intervention tool for promoting the use of the paretic limb.

2 METHODS

2.1 Equipment

The RGS-Wear is a wearable system for the continuous monitoring of arm use in hemiparetic stroke patients. It is composed by a pair of bracelets and a smartphone (Sony Xperia Z3 Compact). The bracelets include a coin-sized Bluetooth-Board (MetaWear, MbientLab, San Francisco, CA.) with integrated accelerometer, a vibrating motor, an ultra bright RGB LED, a battery, and a wristband (Fig. 1). The accelerometer is a Freescale MMA8452Q: a smart low-power, three-axis, capacitive micromachined accelerometer with a resolution of 12 bits. Data recordings from each accelerometer are continuously monitored and sent through Bluetooth to a paired smartphone, which demands the patient to carry the smartphone with him or her throughout the day. For this purpose the participants were equipped with a holding bag for the phone to be placed at the waist.

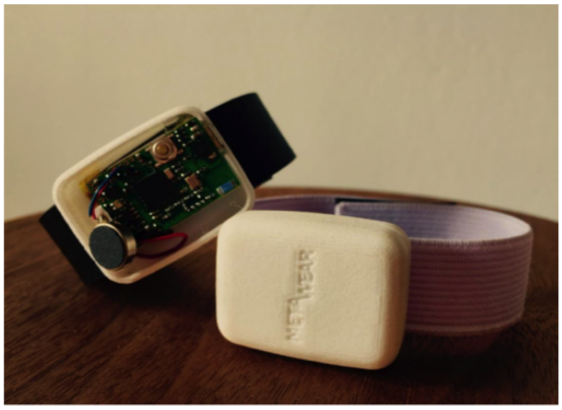

Figure 1: Prototype wearable bracelets integrating the MetaWear board and Velcro straps. the MetaWear board includes a low-power, 3-axial capacitive micromachined accelerometer, RGB LEDs, and a coin vibrating motor.

2.2 Quantification of Arm Use

For monitoring purposes, the acceleration data from each device (left bracelet, right bracelet, and smartphone) is sampled at 50Hz for each directional dimension. In order to derive from these data some meaningful quantification of arm use, we followed a number of steps. First, over a one minute epoch, we computed the mean squared sum of the acceleration:

$$\beta = \sqrt{\alpha_x^2 + \alpha_y^2 + \alpha_z^2} \quad (1)$$

This measurement represents a rough index of the amount of movement of the object to which the accelerometer is attached. This method has been shown to be an adequate approximation of Energy Expenditure (EE) in comparison to measurements derived from the heart's electrical activity, muscle activation, and oxygen consumption (van der Pas et al., 2011;

Tsurumi et al., 2002). Next, in order to provide feedback to the user, we defined the change in the EE of the paretic arm as:

$$\delta = \frac{\gamma_p - \gamma_0}{\gamma_p} \cdot 100 \tag{2}$$

where γ_p refers to the mean activity of the paretic arm per hour, γ_0 corresponds to the mean activity of the paretic arm at baseline, and arm activity is given by the difference between the activity of the corresponding arm β_a and the activity of the body β_b:

$$\gamma = \beta_a - \beta_b \tag{3}$$

$$\text{where } [\gamma]^+ = \begin{cases} \gamma, & \text{if } \gamma > 0 \\ 0, & \text{if } \gamma < 0 \end{cases}$$

In addition, in order to monitor arm balance, we compute the ratio between the daily mean activity of the paretic γ_p, and non-paretic arm γ_{np}. Thus arm balance is given by:

$$\theta = \frac{\gamma_p}{\gamma_p + \gamma_{np}} * 100 \tag{4}$$

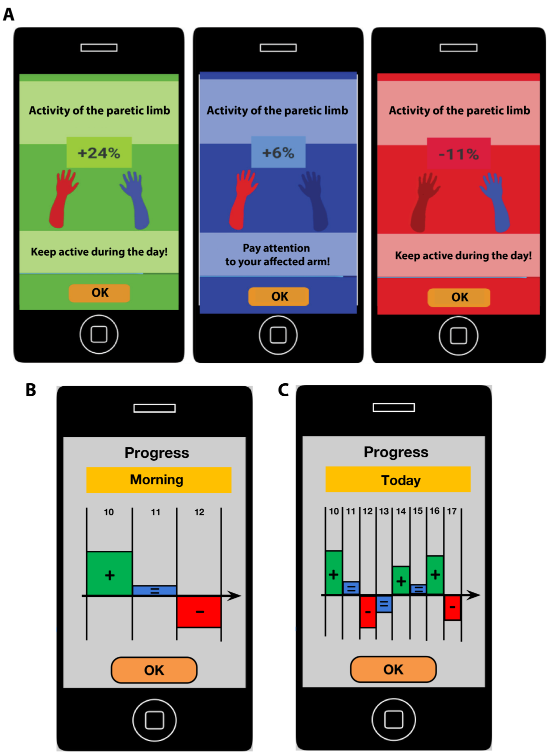

Figure 2: Graphical interface for feedback delivery. A. Types of feedback according to the change in EE by hour (Hourly Feedback). B. Example of Review Feedback showing the change in Energy Expenditure (EE) achieved during the morning (from 10 to 13 hours). C. Example of Review Feedback delivered at the end of the day, showing the change in EE by hour along the daily session (from 10 to 19 hours).

2.3 Feedback Design

The main objective of this study was to evaluate the influence of feedback of performance on arm use. Therefore, we first explored how to deliver this type of information to the patient in an efficient and meaningful manner. The design principles shaping RGS-Wear were derived from the Self-Determination Theory proposed by Ryan et al. (Ryan et al., 2008). This theory defines three main behavioral mediators, which determine a patient's self-engagement within the process of Health Behavior Change:

1. **Autonomy:** the patient's degree of Self-engagement as the willingness to change due to the self-referenced value of the targeted behavior.

2. **Competence:** the individual's capacity to afford a change.

3. **Relatedness:** the relation of the patient with the practitioner, who facilitates the other two mediators.

Based on these principles, the RGS-Wear was designed to serve as a rehabilitation device for self-reinforcement. The incoming feedback messages are delivered through the vibration of both the smartphone and bracelets. Additionally, the phone displays a sound signal, whereas the bracelets' LEDs blink in red, green or blue, according to the improvement category achieved (Table 1). Every message has a confirmation button, which should be pressed to confirm its reception. The following subsections describe in detail these feedback messages.

2.3.1 Hourly Feedback

The Hourly Feedback was designed to be simple and effective as the user derives all information about improvement in use with a short glance at his smartphone (Fig. 2A). A percentage indicates the mean change in the EE of the paretic limb in respect to baseline that was achieved within the previous hour (mean δ, see Eq.2). This type of messages are accompanied by an illustration of the upper-limbs. Beneath, a comment window shows different motivational sayings (e.g. "Stay active along the day."). Considering not to generate pressure, the text appears as a general request to stay active within the day, regardless of the numerical result shown.

This feedback was designed to support the patient's self-engagement and increase the value of using the paretic arm in the performance of iADLs. This type of feedback is thus tightly related to the concept of *Autonomy* proposed by the Self-Determination Theory (SDT). In this line, the display of a percentage

Table 1: Feedback Categories.

Result	Above 10%	Between 10% and -10%	Below -10%
Category	Positive	Neutral	Negative
Signal in bracelets	Green blinking light	Blue blinking light	Red blinking light
Signal in smartphone	Positive green operator	Positive blue operator	Negative red operator

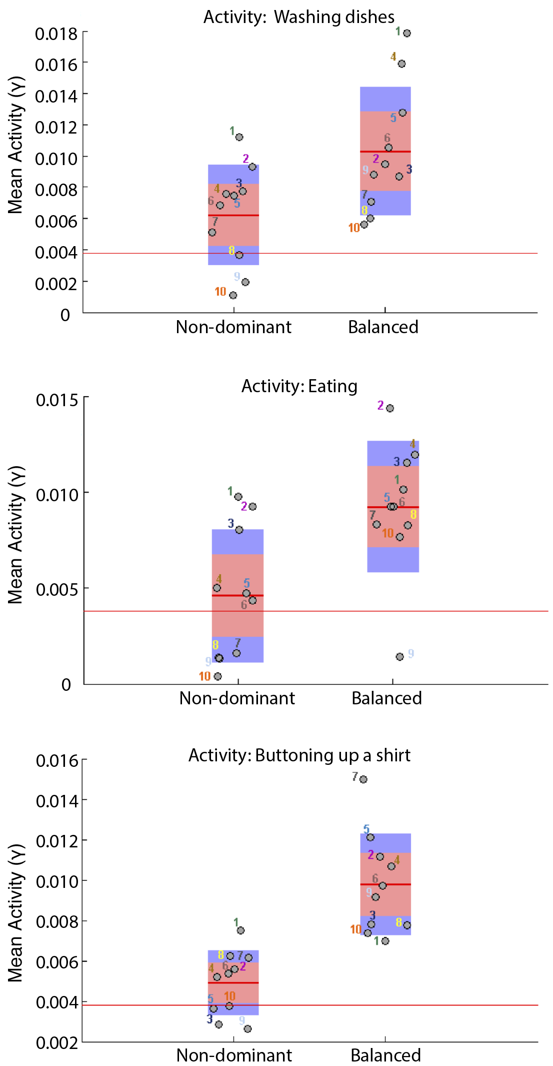

Figure 3: Averaged activity of the non dominant arm, for each subject, achieved during the execution of three iADLs (Wash de dishes, eating, and buttoning up a shirt) under two different conditions. During the Restricted condition, the use of the left limb was limited. During the Balanced condition, the participant was encouraged to use both arms. Red horizontal lines indicate the inactivity threshold.

improvement in use provides a target oriented self-regulation.

2.3.2 Review Feedback

The Review Feedback displays a summary of the Hourly Feedback in session intervals (Fig. 2B), thus providing knowledge of progress. In this study, RGS-Wear was pre-programmed to monitor 9 consecutive hours a day. Daily recordings were partitioned in a morning, afternoon, and night sessions, and each of them had a duration of 3 hours. Review Feedback was provided at the end of each session and at the end of the day, displaying the hourly mean activity level of the paretic arm in a graphical chart. The rational for this feedback was to meet the patients' psychological need of *Competence* by presenting an overview of performance over time.

2.3.3 Instructions Slides

The RGS-Wear daily protocol is initialized at 10 a.m. by presenting a number of welcoming slides accompanied by an alarm sound that signalizes the beginning of the monitoring.

2.4 Experimental Paradigm

In order to assess the reliability of the RGS-Wear for capturing differences in arm use, we first conducted an experiment on humans with no neurological impairments. We instructed participants to perform four iADLs (washing the dishes, eating, buttoning up a shirt, and walking) while wearing the RGS-wear bracelets. Each activity had a duration of 3 minutes. All activities were performed twice: first, participants were asked to use their left arm with reduced intensity as they would normally do (non-dominant condition), and second, bi-manual execution was encouraged (balanced condition).

After validating RGS-Wear as a monitoring tool, we designed an experimental paradigm to explore the potential of RGS-Wear for promoting the use of the paretic limb in stroke patients. Participants were instructed to use the RGS-Wear system at home for five consecutive weekdays, from 10 to 19 o'clock, except when bathing. The experiment was divided in three phases: pre-test, intervention, and post-test. Due to the ubiquitous presence of the device, the sensation of being under observation could be cued and may

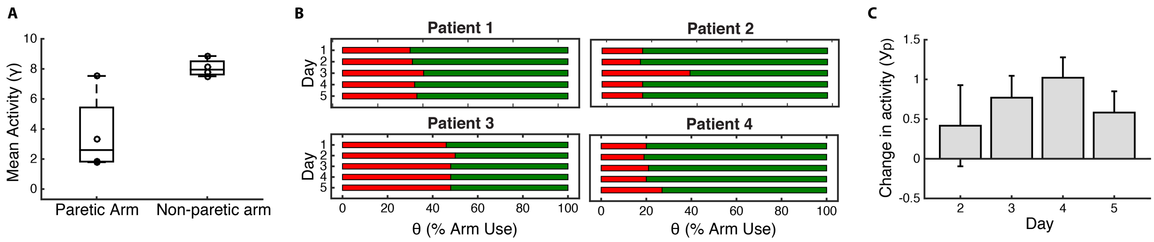

Figure 4: Quantifying behavioral changes. A. Difference between arm activity during baseline (day 1). B. Arm Use Balance between the paretic (red) and non-paretic arm (green) per day exhibited by each patient. C. Mean change in the activity of the paretic limb with respect to baseline, across the three days of intervention (day 2-4), and post-test (day 5). The y-axis refers to the change from baseline averaged across subjects.

lead to an over-encouraged behavior. In order to control for this effect, patients were instructed to wear the system everyday but did not receive any type of feedback at day 1 (i.e. pre-test or baseline) and day 5 (i.e. post-test) of the experimental protocol. From day 2 to day 4 (i.e. intervention phase), the RGS-wear system provided Hourly Feedback and Review Feedback to the patient. Before (day 1) and after the experiment (day 5), participants fulfilled an Intrinsic Motivation Questionnaire (IMQ). The IMQ consisted in 7 statements designed to capture changes in the patient's perceived competence and effort when using the paretic limb (see APPENDIX, Questionnaire on Intrinsic Motivation). Answers were reported using a 7-point Likert Scale, ranging from Strongly Disagree to Strongly Agree. In addition, a Usability Questionnaire (UQ) was administered at the end of the experimental protocol (day 5) to assess the system's acceptability in terms of its hardware design, graphical user interface (GUI), interaction design, and perceived efficacy (see APPENDIX, Questionnaire on Usability). In this questionnaire, answers were reported using a 5-point Likert Scale. The ethics committee of clinical research of the Parc de Salut Mar approved experimental guidelines.

2.5 Participants

For the validation of the accelerometers-based measurement of arm use, we recruited 10 right-handed volunteers without neurological impairments (5 females, mean age = 26.6 ± 2.59 years old). Secondly, in order to explore the clinical impact of the RGS-Wear, five chronic stroke patients were first approached by a doctor from the rehabilitation department of Hospital Esperança in Barcelona to determine their interest in participating in this research project. Selected patients met the following inclusion criteria: 1) Ischaemic strokes (Middle cerebral artery territory) and hemorrhagic strokes (intra-cerebral). 2) Mild-to-moderate upper-limbs hemiparesis. 3) Age between 45 and 85 years old. 4) Absence of any major cognitive impairments. 5) Frequent smartphone user. One patient refused to participate. The remaining four patients (4 males, 70.5 ± 6.76 years old) were included in the study. Prior to the experiment, all participants signed informed consent.

3 RESULTS

3.1 Accelerometer-based Measurement of Arm Use

In order to evaluate the reliability and validity of accelerometry for measuring arm use in non-impaired subjects, we examined the subjects' non-dominant arm activity under 2 different conditions (non-dominant and balanced), in four different iADLs (washing the dishes, eating, buttoning up a shirt, and walking). As we expected, in the non-dominant condition, performance of iADLs was characterized by the decreased activity of the left hand (Fig. 3). In the walking task, activity measures fell below the inactivity level in both conditions, indicating that the mean acceleration of each hand was not superior to the mean body acceleration. These results validate the reliability of the RGS-Wear system for capturing the amount of use of the upper-limbs in iADLs.

3.2 Effects on Amount of Use

After exploring the use of wearable devices for arm use monitoring, we proceeded to investigate its applicability as an intervention tool. Since amount of use and recovery are tightly coupled, using wearable devices to induce an increase in arm use could have a positive impact in motor recovery. One approach to pursue this idea is to use wearable devices to expose the patient to arm movement related feedback, thus increasing the intrinsic motivation for integrating the paretic limb in the performance of iADLs.

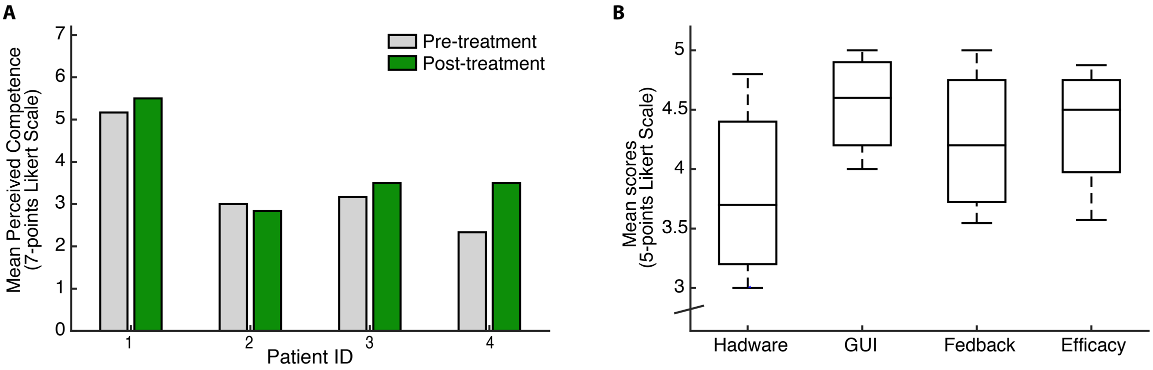

Figure 5: Responses from questionnaires. A. Average scores quantifying the patient's intrinsic motivation for using the paretic limb in the performance of iADLs. B. Mean scores for each category assessed by the usability test.

To address this question, we first compared the mean levels of Energy Expenditure (EE) estimated at baseline (day 1) for each arm and subject (β in Eq. 1). As expected, we observed that all patients reached higher EE values when using the less affected limb (Figure 4A). Patient 3, who presented with mild hemiparesis, showed a highly balanced arm use, reaching a mean EE value of 7.53 for the paretic limb, and 8.85 for the non-paretic limb. These preliminary results support the use of accelerometry for quantifying arm use in hemiparetic stroke patients. Next, we analyzed the change in arm use balance respect to baseline (day 1). Although we observed differences between patients, the estimation of arm balance values remained stable within subjects (Fig. 4B). Overall we found a general increase in the Arm Use Balance, suggesting an increased integration of the affected limb in the performance of iADLs. However, since Arm Use Balance is a relative measurement (see Eq. 4), it does not express the amount of movement. A patient could therefore achieve positive improvements in Arm Use Balance by only limiting the movement of the non-paretic limb. In order to take into account the patient's amount of arm movement, we analyzed the change in the activity of the paretic limb with respect to baseline (day 1). Interestingly, results revealed an increase in activity which accumulated along the three days of intervention (Fig. 4C). Even though we observed a drop in activity at day 5 (post-test), when no feedback was delivered any more, arm use improvements were still partially retained.

3.3 Effects on the Patients' Intrinsic Motivation

We analyzed the influence of the RGS-Wear paradigm on intrinsic motivation by comparing the scores reported by the four patients before (day 1) and after the treatment (day 5). We observed that, after treatment, 3 out of 4 patients exhibited higher intrinsic motivation to use the paretic limb (Fig. 5A). According to the Self-Determination Theory, this subjective improvement may emerge from the repetitive exposure to knowledge of progress, a factor tightly linked to the behavioral mediator *Autonomy*.

3.4 Usability

We studied the usability aspects of the RGS-Wear through a questionnaire that was divided into 4 categories (5 questions each): hardware, graphical interface, feedback, and perceived efficacy. Overall, the patients' ratings were above 3 (neutral), suggesting that the system's design was generally accepted. Interestingly, we noticed that the rating of hardware features was notably lower in comparison to the other categories. When we explored the patient's answers in detail, we found that those statements referring to the comfort of putting the bracelets on received lower scores from most of the patients.

4 CONCLUSION AND DISCUSSION

We have presented results from a pilot study supporting the benefits of wearable-based feedback on arm use. Our results suggest that frequent exposure to direct feedback about arm use promotes the integration of the paretic limb in the performance of iADLs. In addition, results from questionnaires revealed that the use of wearable devices may influence positively the patient's intrinsic motivation for using the affected arm.

The work we presented in this article is the continuation of our previous work on the use of new technologies for counteracting learned non-use. In a recent study, we used a neurologically grounded computational model of motor recovery (Han et al., 2008) that can predict the positive influence of reinforcement-based training on arm use (Ballester et al., 2015a). In this work, we proposed that hand selection is modulated by two main parameters: expected success and effort. We conducted two clinical experiments that suggested that by increasing the value of using the paretic limb (expected success) and decreasing its cost (effort) we can promote its spontaneous use (Ballester et al., 2015b) and boost recovery (Ballester et al., 2015a). Based on these findings, we now explore how wearable devices could allow the ubiquitous delivery of a variant of Reinforcement-Induced Movement Therapy (RIMT).

Our results suggest that monitoring the amount of arm use and providing knowledge of progress could provide multiple benefits: 1) it may allow the patient to set-up implicit goals, and 2) it may increase the value of using the paretic limb, therefore biasing effector selection patterns. Thus, the repetitive exposure to reinforcement-based feedback after performance may modify both the individual's goals and self-representation. While the first may provide the necessary context for the introduction of behavioral changes, the second may consolidate them. Interestingly, a recent controlled clinical trial including 156 acute stroke patients evaluated the clinical impact of using wearable triaxial accelerometers at both ankles and recording continuously for 8 hours per day (Dorsch et al., 2015). Once a week, participants in the experimental group also reviewed the results of their summary activity graphs with the therapists. Results indicated that the group receiving the augmented feedback did not spend a greater amount of time walking. This findings seem to be contrary to our results. This difference can be explained by three factors: 1) the RGS-Wear provided frequent daily feedback about performance and progress, 2) the patients using RGS-Wear reviewed their activity feedback autonomously and 3) the RGS-Wear was applied on the upper-extremities while Dorsch, et al. focused in gait and lower-extremities.

Future work aims at validating the impact of RGS-Wear in arm use by conducting a controlled longitudinal clinical study on acute stroke patients. In this study we plan to measure the retention of improvements in arm use induced by the RGS-Wear, and its consequent influence on motor recovery.

ACKNOWLEDGEMENTS

We would like to acknowledge all patients who participated in this study. Special thanks to Dr. Boza Gómez for her assistance in recruiting stroke patients. This project was supported through ERC project cDAC (FP7-IDEAS-ERC 341196), EC H2020 project socSMCs (H2020-EU.1.2.2. 641321) and MINECO project SANAR (Gobierno de Espaa).

REFERENCES

Ballester, B. R., Maier, M., Duff, A., San Segundo, R., Castañeda, V., and Verschure, P. (2015a). Reinforcement-Induced Movement Therapy: A novel approach for overcoming learned non-use in chronic stroke patients. In *Proceedings of the International Conference on Virtual Rehabilitation. In press.*, pages 1–6.

Ballester, B. R., Nirme, J., Duarte, E., Cuxart, A., Rodriguez, S., Verschure, P., and Duff, A. (2015b). The visual amplification of goal-oriented movements counteracts acquired non-use in hemiparetic stroke patients. *Journal of neuroengineering and rehabilitation*, 12(1):50.

Dorsch, a. K., Thomas, S., Xu, X., Kaiser, W., Dobkin, B. H., Emara, T., Edwards, D., Fonzetti, P., Maasch, J., Lee, S.-G., Owolabi, M. O., Hamzat, T. K., LeBlanc, C. J., Morse, R., Swaminathan, N., Karatas, G. K., Boza, R., Brown, a. W., Miyai, I., Kawano, T., Chen, S.-Y., Hanger, H. C., Zucconi, C., Mammi, S., Ghislanzoni, C., Juan, F., and Lang, C. E. (2015). SIRRACT: An International Randomized Clinical Trial of Activity Feedback During Inpatient Stroke Rehabilitation Enabled by Wireless Sensing. *Neurorehabilitation and Neural Repair*, 29(5):407–415.

Gubbi, J., Rao, A. S., Fang, K., Yan, B., and Palaniswami, M. (2013). Motor recovery monitoring using acceleration measurements in post acute stroke patients. *Biomedical engineering online*, 12:33.

Han, C. E., Arbib, M. A., and Schweighofer, N. (2008). Stroke rehabilitation reaches a threshold. *PLoS computational biology*, 4(8):e1000133.

Hidaka, Y., Han, C. E., Wolf, S. L., Winstein, C. J., and Schweighofer, N. (2012). Use it and improve it or lose it: interactions between arm function and use in humans post-stroke. *PLoS computational biology*, 8(2):e1002343.

Lai, S.-M., Studenski, S., Duncan, P. W., and Perera, S. (2002). Persisting consequences of stroke measured by the Stroke Impact Scale. *Stroke*, 33(7):1840–1844.

Markopoulos, P., Timmermans, A. A. A., Beursgens, L., Van Donselaar, R., and Seelen, H. A. M. (2011). Us'em: The user-centered design of a device for motivating stroke patients to use their impaired arm-hand in daily life activities. In *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*, pages 5182–5187. IEEE.

Noorkõiv, M., Rodgers, H., and Price, C. I. (2014). Accelerometer measurement of upper extremity movement after stroke: a systematic review of clinical studies. *Journal of neuroengineering and rehabilitation*, 11(1):144.

Ryan, R. M., Patrick, H., Deci, E. L., and Williams, G. C. (2008). Facilitating health behaviour change and its maintenance: Interventions based on self-determination theory. *European Health Psychologist*, 10(1):2–5.

Taub, E. and Uswatte, G. (2003). Constraint-induced movement therapy: bridging from the primate laboratory to the stroke rehabilitation laboratory. *Journal of Rehabilitation Medicine*, 35:34–40.

Tsurumi, K., Itani, T., Tachi, N., Takanishi, T., Suzumura, H., and Takeyama, H. (2002). Estimation of Energy Expenditure during Sedentary Work with Upper Limb Movement. *Journal of occupational health*, 44(6):408–413.

Uswatte, G., Foo, W. L., Olmstead, H., Lopez, K., Holand, A., and Simms, L. B. (2005). Ambulatory monitoring of arm movement using accelerometry: an objective measure of upper-extremity rehabilitation in persons with chronic stroke. *Archives of physical medicine and rehabilitation*, 86(7):1498–1501.

Uswatte, G., Taub, E., Morris, D., Light, K., and Thompson, P. A. (2006). The Motor Activity Log-28 assessing daily use of the hemiparetic arm after stroke. *Neurology*, 67(7):1189–1194.

van der Pas, S. C., Verbunt, J. A., Breukelaar, D. E., van Woerden, R., and Seelen, H. A. (2011). Assessment of arm activity using triaxial accelerometry in patients with a stroke. *Archives of physical medicine and rehabilitation*, 92(9):1437–1442.

Wang, Q., Chen, W., and Markopoulos, P. (2014). Literature review on wearable systems in upper extremity rehabilitation. In *IEEE-EMBS International Conference on Biomedical and Health Informatics (BHI)*, pages 551–555. IEEE.

APPENDIX

Questionnaire on Intrinsic Motivation: 1- Integrating the affected in the performance of activities of daily living allows me to be more independent. 2- I'm quite competent when I use my affected arm. 3- It's really tiring to use the affected arm in my activities of daily living. 4- I feel secure when I use the affected arm for eating. 5- I feel secure when I use the affected arm for washing the dishes. 6- I feel secure when I use the affected arm for dressing up. 7- How much do you use the affected arm?

Questionnaire on Usability: 1- It was easy to put on the bracelets without help. 2- It was easy to put on the smartphone without help. 3- It was comfortable to wear the bracelets. 4- It was comfortable to wear the smartphone. 5- It was easy to move the affected arm while wearing the bracelets. 6- It was easy to hear the messages alarm on the smartphone. 7- It was easy to notice the bracelets vibrations and lights. 8- It was easy to understand the messages on the screen of the smartphone. 9- It was ease to press the buttons on the screen of the smartphone. 10- It was easy to read the texts appearing on the screen of the smartphone. 11- I think I missed more than 3 messages a day. 12- Sometimes the messages were annoying. 13- Sometimes the messages scared me. 14- The hourly feedback about the amount of movement was correct. 15- Feedback about the amount of arm movement across days was correct. 16- I think the messages were accurate in reporting my activity. 17- I think the levels of activity reported by the messages were lower than my real activity level. 18- I think the levels of activity reported by the messages were higher than my real activity level. 19- There were too many messages along the day. 20- I would like to receive more messages.