A Healthcare Wearable for Chronic Pain Management. Design of a Smart Glove for Rheumatoid Arthritis

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Abstract: Chronic diseases like Rheumatoid Arthritis affect everyday life of people at multiple scales and require continuous medications and physical therapy for alleviating the symptoms. Wearable technologies offer promising benefits in management of chronic diseases with at home rehabilitation possibilities. This research explored the design process of an e-textile based smart glove that can be used by Rheumatoid Arthritis patients in home environment to reduce pain by applying electrical stimulation therapy and limit hand deformities with textile based splint structures. The whole design process was carried out in close collaboration with medical professionals and sufferers of the disease through iterative prototyping and testing. The multi-disciplinary nature of the smart glove development required a framework for design research covering medical and physiological considerations, textile and electronics technology, and manufacturing methods. The implementation of the design required comfort characterization tests for textiles, electrical characterization tests for e-textile structures and clinical trials.

Keywords: Wearable technology, Smart glove, Pain management, Design process

1. Introduction

Wearable technologies are redefining the way people live from fitness, entertainment to work and healthcare. Wearable technologies are especially disrupting the traditional healthcare as care is being brought to patient rather than patient visiting a medical facility for care. Use of wearable technologies in healthcare is shifting the focus from treatment to prevention, from general to personalized medical care and from hospitalization to at-home monitoring and rehabilitation. As the healthcare has been experiencing new frontiers, design for next healthcare requires close collaboration among designers, engineers, medical staff, patients and caregivers.
In this study, we report the design process of a wearable technology for at home rehabilitation of a chronic autoimmune disease, Rheumatoid Arthritis (RA), in close collaboration with medical staff and patients. RA is a systemic inflammatory disorder that primarily affects small joints of hands. RA causes painful swelling of lining of joints and stiffness in morning hours and can eventually result in bone erosion and joint deformity and thus hampers daily activities of sufferers. Currently there is no cure for RA but it is commonly treated with medications and physiotherapy to minimize symptoms and slow down progress of the disease. Even though RA is widely observed in later ages, it can affect people at any age including children. RA effects 0.5-1% of World population (Silman & Hochberg, 2001) and supporting its treatment in home environment by using a smart therapeutic glove will increase patients’ performance in daily practices and personal care.

We designed an e-textile based smart glove that can be used by RA patients in home environment to reduce RA symptoms by applying electrical stimulation therapy which uses stimulating low-voltage electrical pulses across the surface of the skin and along the nerve strands for pain relief. A field research is conducted with RA patients, physiotherapists and medical doctors in a University Hospital to develop an in-depth understanding of the needs and limitations of patients and available treatment alternatives. A unique smart glove that pays particular attention to functionality and aesthetics providing pain relief via electrical stimulation, joint immobilization and compression is developed. Textile electrodes and transmission lines that deliver signal, realized with silver conductive threads using an industrial CAD embroidery machine, are embedded into the smart glove.

2. Literature review

2.1. Design of Wearables

Wearables can be simply defined as technology that can be worn on the body as an accessory or as an electronic textile material used in clothing. Electronic textiles (e-textiles) are textiles with unobtrusively built-in electronic functions woven into them presenting physical flexibility (Tao, 2005; Stoppa & Chiolerio, 2014). Similarly, smart textiles is a terminology used to define fibres, filaments, yarns as well as knitted, woven or nonwoven structures that can interact with the environment (Stoppa & Chiolerio, 2014). In these applications, components such as electrodes, sensors or actuators as well as connections are embedded in the textile structure.

The study of wearables crosses boundaries between many disciplines from design to engineering, medicine and social sciences. According to McCann, Hurford and Martin (2005) this new discipline embraces creativity, aesthetic awareness and technical innovation and requires understanding of usability, manufacture, fashion, consumer culture and end user needs. Authors discuss the design of wearables under Demands of the Body, Demands of the Activity/End use, Demands of Culture and Aesthetic Considerations titles. Demands of the Body is about the characteristics of the material worn on the body and its interaction with the body. Thermal regulation, movement and fit are human factors aspects to be considered which are at the same time related to fibres, yarns, textile constructions, membranes and coatings, and finishes applied to textiles. Bouwstra et. al (2009) defined similar aspects in their study where they report the iterative design process of a neonatal monitoring wearable. According to authors neonatal monitoring is a multi-disciplinary area which involves integration of knowledge from medical science, design, technology and social study. The process starts with information search on technical aspects such as unobtrusive ECG monitoring and intelligent textiles, and user needs. Once requirements are derived from the information search
phase, design ideas are developed simultaneously with technology tests and user tests. Authors define the three aspects of technology, user need and design as strongly interwoven along the whole design process. Apart from the reliability of technology, wearability is concluded to be the vital aspect in the success of the neonatal wearable.

While above cited studies have focused on the design of wearables from the physical perspective Lee and Coughlin (2015) approach the issue from a more holistic perspective including social contexts of use, delivery and communication channels. Authors developed a framework of 10 factors that should be considered in the design of wearables that affect their adoption by users; value, usability, affordability, accessibility, technical support, social support, emotion, independence, experience, and confidence.

2.2. Rheumatoid Arthritis and Wearables for Hand

Rheumatoid arthritis (RA) is a chronic, auto immune disease that mostly effects small joint of hands and feet as well knee and wrist joints. RA causes pain, joint stiffness and swelling leading to joint deformations, impaired hand function and difficulty with daily activities (Nasir, Troynikov & Massy-Westropp, 2014). Hand is one of the most complicated anatomical structures in the human body that can perform tasks such as grip, sensory feedback and motor coordination (Dianat et al., 2012). Therefore, the inflammation, pain and joint deformation caused by RA affects daily activities such as tying a lace, buttoning, grooming, brushing teeth, opening doors, turning keys and many others.

RA is treated with physical therapy modalities such as hot and cold thermotherapy, ultrasound and electrical stimulation in addition to pharmaceuticals. Splints and braces are widely used in the treatment of joint deformities. Therapy gloves are also recommended by occupational therapists as another alternative in alleviating symptoms related to RA. According to the review by Nasir, Troynikov & Massy-Westropp (2014) there are many types of therapy gloves available in the market like thermal gloves to provide warmth, glove splints to provide support and gloves that provide compression. One theory on why therapy gloves provide symptomatic reliefs is that gloves provide warmth and the increased skin and joint temperatures lead to increase in blood flow and thus effective supply of oxygenated blood and nutrients to the inflamed tissues (Sluka et al., 1999). Compression provided by therapy gloves is reported to decrease swelling of joints and to increase the rate of finger motion and grip strength (McKnight & Kwoh, 1992). Compression provided by a therapy glove speeds blood flow to a specific area increasing circulation. In addition, compression can provide extra support and help to control sudden movements that can cause bursts of pain.

There has been many research on smart glove technologies for physical therapy and rehabilitation purposes. This area of research especially focuses on rehabilitation of stroke patients. Smart rehabilitation gloves that help to do controlled and repeated flexion and extension exercises in virtual environment for stroke patients to regain their motor skills are designed (Bouzit et.al., 2002; Burdea et.al., 1992; Popescu et.al., 2000; Boian et.al., 2001; Adamovich et.al., 2004). Glove based systems that can measure motion in hand joints during dynamic tasks to replace the use of goniometers are developed (Dipietro, Sabatini & Dario, 2003; Quam, Williams, Agnew & Browne, 1989; Micera et.al., 2003; Williams et.al, 2000; Su et.al., 2003). However, based on the literature review it is realized that there exists no research that focuses on designing a smart glove for physiotherapy of RA sufferers. This study reports the multifaceted design process of an e-textile based, multi-functional therapy glove for RA that delivers electrical stimulation for pain management and provides support to treat joint deformities.
3. The Design Process

The smart glove for RA is developed as a result of an iterative and multifaceted design process that brings together industrial design, engineering and medicine fields as illustrated in the following framework.

![Figure 1. The process flow framework for the design of wearables.](image)

The design process for the RA glove started with a comprehensive research phase with the goal gain an in depth understanding of the disease from multiple perspectives, previous related research and available material technology. A two-phased field research is conducted in a University Hospital with physiotherapists, rheumatologists and patients to understand the symptoms of the disease and commonly applied treatment methods. Literature on the medical research about RA disease is reviewed to build the required medical literacy for effective communication with medical professionals prior to the field research. At the first phase of the field research, physiotherapists and rheumatologists are interviewed about the treatment alternatives and participatory observations in the physical therapy unit are conducted. At the second phase of the field research RA patients are interviewed about their experiences related to the disease including home remedies and treatments they personally developed. In depth material research and literature research on related technologies accompanied the field research. Textile materials including fabrics, membranes and laminates and conductive yarns are explored to determine the suitable alternatives for glove prototype development. Literature on electronic textiles and smart garments in engineering and design fields, RA disease and hand anatomy are reviewed. The iterative and in-depth process of research yielded many design criteria, which are transformed into a mind map illustrating the relationship among them.

The second phase of the smart glove design was an iterative, intense prototyping and testing period. Two types of prototypes were simultaneously developed and tested at this stage. Idea prototypes about the form and physical functionalities of the glove are developed and tested for wearability and usability feedback from the patients. Eleven idea prototypes are developed and tested consecutively with the testing of each prototype yielding to improvements and new ideas for the next one. Technology prototypes on the other hand are used to develop and test the textile electrodes and textile signal transmission lines, and to optimize the manufacturing methods for realizing the electrical stimulation therapy. The textile materials used in these prototypes are also tested for their thermal characterization. At the end of this stage, idea prototypes are narrowed down to best
solutions using Pugh matrices while technology prototypes are narrowed down to optimum performing e-textile structures. The following criteria determined the best solutions: Ease of donning/doffing, adjustability, suitability for daily use, prevention of hand deformities, pain management, ease of production, physiological comfort, ease of movement, suitability for placing of electrical components, and insulation.

The third phase of the smart glove design process is a focused prototyping and testing period where ideas and technologies developed in the first round of prototyping are merged into fully-functional working prototypes which are clinically tested for their effectiveness in the rehabilitation of the disease. This phase is conducted in very close collaboration with medical professionals and patients to gather as much feedback as possible to update and finalize the smart glove design.

4. The Smart Glove for Rheumatoid Arthritis

Adherence to wearing a glove on a daily basis requires high motivation from a patient. Therefore, it is crucial that the smart glove delivers effective treatment to alleviate the symptoms of RA disease, smart glove is comfortable and not disturbing to the peripersonal space of the wearer and finally smart glove offers intuitive and simple use experience.

During the design process, each prototype is developed to seek solutions to the following three problems: 1. pain control through compression and electrical stimulation, 2. treatment of joint deformities, 3. Wearability.

4.1. Treatment: Pain Management

Pain management in a smart glove for rehabilitation of RA is approached from two perspectives: delivery of low voltage electrical pulses to pain areas on hand and the delivery of the necessary amount and distribution of compression to the hand.

The smart glove design is developed to apply electrical stimulation therapy with stimulating low-voltage electrical pulses across the surface of the skin and along the nerve strands for pain relief. The electrical pulses disrupt the pain signals created by body parts affected from pain and thus decrease the pain sensation. Compared to pharmaceuticals used for pain management, use of electrical stimulation does not cause any side effects and provide instant pain relief while in use. In order to embed electrical stimulation function in the textile surface of the glove multiple technology prototypes are developed and tested. Embroidery technique is used to achieve the textile electrodes and signal transmission lines by attaching conductive threads to a ground, non-conductive textile structure. This technique allows precisely specifying the stitching pattern in a computer-aided design (CAD) environment, from which any number of articles can be sewn under machine control (Mac, Houis & Gries, 2004). The textile electrodes consisted of silver coated polyamide threads embroidered in an optimized pattern as 15mm diameter circles. The signal transmission lines are also realized using embroidery technique to connect the electrodes with each other and to the control unit that delivers the electrical pulses. The electrodes and signal transmission lines are tested for their resistance and signal to noise ratios.
Parallel to development of electronic textile structures, idea prototypes are developed to utilize compression in pain management for RA. The field research showed that patients consciously or unconsciously apply compression to pain areas either by taping or pressing with their fingers. The literature review on medical applications of compression wear for pain management also justified this finding. The material research resulted in compression membranes that are widely used in athletic wear. These membranes are laminated on the textile surface to exert pressure on certain body parts. Lamination of the compression membranes alters the stretch characteristics of the fabric and thus the alternating stretch on the textile surface exert pressure to skin. As a result, compression membranes are both utilized along finger joints for pain management and for preventing physical joint deformation. The same membranes are also used for insulating the signal transmission lines and textile electrodes. The lamination of compression membranes on the glove structure are tested by patients for effectiveness in treatment and also by means of electrical characterization methods to understand its effect on resistance and signal performance of the electronic textile structures.

4.1. Treatment: Physical Deformities

In a joint affected by RA, inflammatory cells of the immune system gather in the lining of the joint, forming a fibrous layer of abnormal tissue that quicken bone erosion, cartilage destruction and damage the surrounding ligaments. The involved joints lose their shape and alignment, resulting in deformities. Commonly observed deformities in fingers during the field trip were boutonniere deformity where the middle finger joint bends toward the palm while the outer finger joint may bend opposite the palm and the swan-neck deformity where the base of the finger and the outermost joint bend, while the middle joint straightens. Ulnar Deviation or Ulnar Drift is another commonly observed deformity of the hands in which there is gradual shifting of the wrist and fingers in an ulnar direction.
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Figure 3. Examples captured during the field research about hands affected from RA deformities.

Metal splints in the form of RA rings apply force in the reverse direction of deformities for treatment. Series of idea prototypes are developed to create a textile based splint effect in the joint locations of the smart glove. Flexible tapes, rigid tapes as well as heavy weight stitching are integrated around the circumference of commonly affected finger joints. However, none of these applications received noticeable positive feedback from patients.

Figure 4. Example ideas for textile based splints.

Based on these failed prototypes it was realized that stretch characteristics of the material integrated around the joints has affect in stabilizing the finger in a desired position and also in providing necessary compression around painful and swollen joints. In the following prototypes splint idea is applied on textile material as cross-shaped applications of compression membranes on exactly top of the finger joints. The lamination of compression membranes received significantly positive feedback from patients.
Next round of idea prototypes targeted the ulnar deviation around the wrist joint. External support in the form of a flexible plastic band is inserted in a pocket created on the glove surface. Wrist is also stabilized by wrapping textile material that extends out from the proximal phalanges of the pinky finger to create an opposite torque to the ulnar deviation. This wrapping method not only stabilizes wrist joints but also functions as a donning/doffing mechanism for the smart glove.

4.2. Wearability

The fit and construction of the therapeutic gloves could influence the patient’s hand movement, sensation and overall comfort (Nasir, Troynikov & Massy-Westropp, 2014). The pattern of the glove has been improved with each iteration of the prototypes to provide the optimum skin contact for the electrodes embroidered on the glove surface and the optimum physiological comfort.

Hand grip is a significant biomechanical criterion that affect daily life routine. During using the smart gloves patients should be able engage in activities that require grip, pinch abilities and dexterity. Therefore, fingertips of the smart gloves are left open as it was highly preferred by the patients.

The smart glove is expected to be worn on a daily basis for at least half an hour. Thermophysiological comfort properties of the glove are also significant wearability parameters. The gloves should not cause physiological discomfort due to excess warmth or sweat production. In addition, interviews with medical professionals revealed that during acute episodes of the RA disease, elevated
temperatures could have negative effect on pain and swelling of the joints. Textile material used in
glove construction is selected based on comparative test results for air permeability and water
vapour permeability tests. A one-way stretch, polyester spacer knit fabric with high breathability
characteristics is employed in the final smart glove prototype.

Easy donning and doffing of the smart glove is a paramount because during wearing process, only
single hand could be in action for dressing the other one. In addition, closure details are critically
important since RA mainly affects the hand’s dexterity in activities such as pulling zippers and
buttoning. Different donning/doffing and closure approaches are tested with patients in different
prototypes. In an earlier idea prototype, zipper was used as a closure option and it was observed that
patients struggled with handling the zipper pull and undoing the zipper due to stretch characteristics
of the knit fabric. Velcro tapes were finally employed to stabilize the smart glove around the wrist.

5. Conclusion

Chronic disease and pain management require consistent day-to-day actions in addition to
continuous visits to healthcare facilities. For patients with Rheumatoid Arthritis at home
rehabilitation of pain and other symptoms associated with the disease is possible with use of a
wearable technology. This study reports the design process of an electronic textile based therapeutic
glove for RA. Designing such a product required understanding and responding to a broad range of
both technical and creative issues such as awareness of aesthetics, garment and textile technology,
electronics and medical literacy. Therefore, the design process started with a multifaceted and in-
depth research phase and heavily relied on patient and expert feedback throughout. Iterative
prototyping both for testing ideas with patients and developed technologies in a laboratory setting
was a paramount. Each prototype variation was built on the knowledge gained from the previous
one and finally both the technology aspect and physical aspects were merged into a fully functional
prototype. After this stage, the glove prototype needed to be tested by patients in clinical trials for
its effectiveness in treating the symptoms of the disease.

Physiological and technological considerations guided the design of the glove. Thermal and tactile
comfort as a well as mobility were critical in making material selections and design decisions. The
technology developed was an e-textile structure that could deliver low voltage electrical pulses to
the joints mainly affected by RA. Computer aided embroidery parameters ad manufacturing process
were optimized to realize electrodes and signal transmission lines using conductive thread. The e-
textile structure was tested for its resistance and signal performance iteratively until best
performance is achieved.

During clinical trials even though patients approached the glove with suspicion initially, all were
willing to try it. Patients were concerned about how the product could enhance their quality of life in
terms of health rather than its appearance. Even though research showed that smart garments are
struggling to gain social acceptance because they fail to follow the norms of social interaction
(Edwards, 2003), with this particular example, users approached the product as an alternative device
to pharmaceutical use.

For future research, we propose that the smart glove can be enhanced with motivational features
such as reminding, warning or encouraging patients for continuous use of the product.
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