Designing smart garments for rehabilitation

DESIGNING SMART GARMENTS FOR REHABILITATION

DI WANG

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Abstract

Wearable technologies for posture monitoring are emerging as a way to support and enhance physical therapy treatment, e.g., for motor control training in neurological disorders or for treating musculoskeletal disorders, such as shoulder, neck, or low back pain. The work presented in this thesis aims to develop fundamental design knowledge regarding designing smart garments for rehabilitation as there are strong implications in the interdisciplinary field of Human-Computer Interaction, Electronic technologies, Industrial Design and Rehabilitation.

We inventoried the interactive wearable systems for movement and posture monitoring during upper body rehabilitation, regarding the sensing technology, system measurements, feedback conditions, system wearability and availability of clinical evidence.

The approach of Research-through-Design guided our design and development of six iterations of the smart garments and motivating feedback in different modalities. The lessons learned and insights gained have triggered the formulation of six design lenses: Function, Accuracy, Wearability, Aesthetics, Interactivity and Hard & Soft connection. Subsequently, we illustrated the key considerations of each lens and how we applied the lenses in our design iterations.

Systems have been evaluated in accuracy compared to the optical tracking system and applicability for shoulder and torso motor control training. The prototypes have been validated for their acceptance by patients and health workers. The system was perceived as highly usable and users were motivated to train with the system.

To conclude, this thesis contributes to a growing body of research regarding the use of wearable solutions for supporting rehabilitation training with a design that has emphasized wearability, ease of use, aesthetic and motivating. We argue that smart garments for upper body posture and movement monitoring technology can be of great value for rehabilitation training

1

Introduction

This is Tom. He is 36 years old and he works as a graphic designer in an internet company. He usually has quite a lot of sedentary work. Last year he started to suffer from serious shoulder pain and needed to go to the rehabilitation center for rehabilitation training twice a week. The therapist reminded him of some important tips: do more training at home, keep a good posture and keep active during your daily life. Tom understood, however, it was challenging!

Figure 1.1 [1] illustrated his experience. In the night, Tom stood in front of the mirror and with one hand he held the brochure demonstrating the training exercise and subsequently raised the impacted arm. "Am I doing this right or not?", "Should I rotate the arm in this way or not", "Oh, I miss my physiotherapist to help me."... Tom couldn't stop thinking these thoughts , and it was hard to feel the training effect after one-day of exercise.

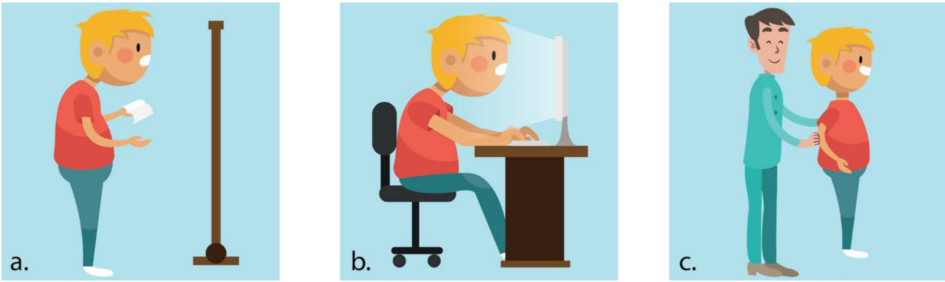


Figure 1.1 Sketches of a user scenario: a) self-training with indeterminacy; b) sedentary life with slouching posture; c) rehab training with therapist's support

In the daytime, Tom prepared a pillow for his back and he reminded himself:" sit straight, straight and straight". However, 3 minutes later, he went back to his normal slouched sitting position once he started to concentrate on his work, and he didn't take notice of his back until his alarm went off that reminded him to walk around. Tom felt some indistinct pain and he was a bit frustrated, "I just couldn't get rid of my habit!", he said.

"Is there anything that can help?" Tom thought.

1.1 Motor Control during Upper-Extremity Rehabilitation

In recent years, there has been a growing need for rehabilitation as the population is ageing, and the prevalence of age-related neurological (e.g. stroke [2]) and musculoskeletal conditions (e.g. neck-shoulder pain or osteoporosis) are growing. Stroke has a high incidence all over the world [3]. In 40 to 50% of stroke survivors, the upper extremity function is affected, leading to a decreased quality of life [4, 5]. In musculoskeletal rehabilitation, shoulder dysfunctions are the third most common complaint [6–8], and in neurological rehabilitation after stroke, shoulder pain affects one-third of stroke patients [9]. Shoulder problems affect functional arm recovery and functional arm use, which decreases daily life performance and autonomy.

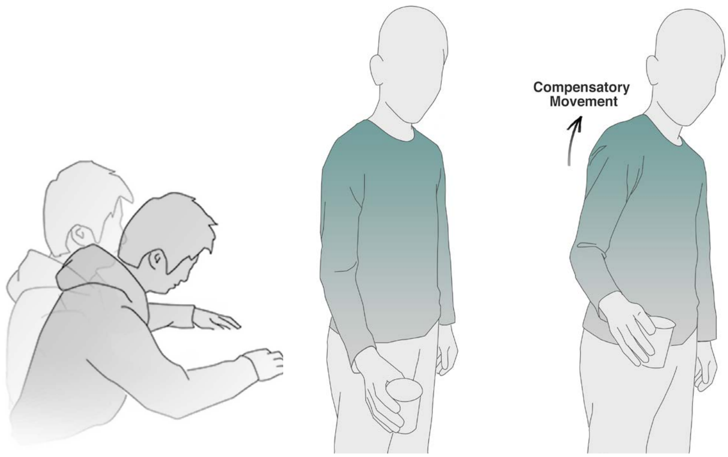


Figure 1.2 The compensatory movement in the task execution

Previous studies [10] indicate that rehabilitation improves function, independence and quality of life [11]. It is typically the task of physiotherapists to supervise the correct execution of exercises and, when necessary, to remind patients to keep to the right posture or to provide corrective feedback. Rehabilitation technology can support training through providing different training input and feedback to help the patients practice tasks, to improve their strength, increase the intensity of exercise and give possibilities on home rehabilitation, which can in turn improve training outcomes.

While in all cases patients have to perform tasks independently or semi-independently, the need arises to make sure they exercise correctly. In this context, one of the most important tasks that requires lots of attention is the detection and prevention of compensation movement [12] during arm-hand training sessions. According to [13], motor compensations were defined 3 different levels and our study focused on the 2nd level which is 'body functions/structure(performance) level'. To be more specific, motor compensation in this level refers to perform an old movement in a new manner or include alternative movement patterns. For example, neurological patients who have a diminished capability to control their arm and hand, tend to develop compensatory strategies [13] in which they use alternative movements and muscle groups to compensate for the reduced ability in their upper extremities: rather than reaching out to grasp an object, they are likely to bend forward to get closer to it and then grasp it (see Figure 1.2a). The complex movement of the shoulder (see Figure 1.3) involves a combination of movements in the scapulothoracic, acromioclavicular, sternoclavicular, and glenohumeral joints. However, in the performance of reaching tasks, patients with shoulder pain at the level of the glenohumeral joint, might develop aberrant movement patterns at the level of the scapulothoracic joint, to compensate for limited glenohumeral motion (see Figure 1.2b). This can be seen in the form of increased scapular elevation in the frontal plane or increased trunk lateral flexion. Compensations might also occur in the sagittal plane, i.e., scapular protraction or trunk flexion [14]. Applying such compensatory strategies can be necessary for getting by in daily life,

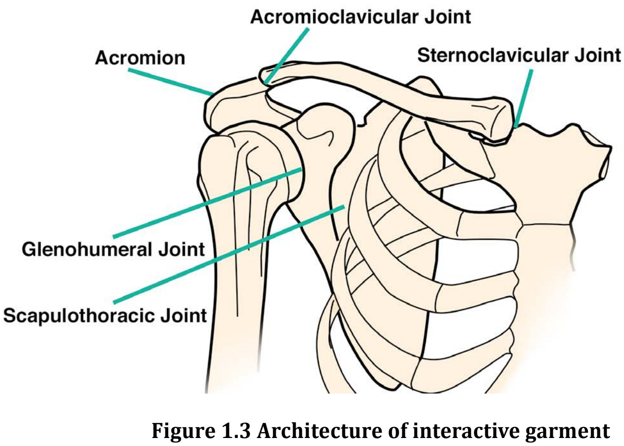


Figure 1.3 Architecture of interactive garment

but during training patients are asked to use their full potential towards 'normal' movement strategies. Compensations may decrease the training efficiency toward recovery [15]. In regular therapy sessions, therapists watch the patients and provide feedback verbally or even manually (a small nudge to show direction and bounds of movement). Notably, the range of movement they will thus allow may be patient-dependent and also may change depending on the progress of a patient, e.g., starting with allowing more compensatory movements and gradually limiting the range of compensation that is permitted.

Thielman et al. [16] found that training with 'restrained trunk motion' during reaching tasks resulted in more significant improvements. Another study of Thielman [17] suggested task-related training with real-time auditory feedback as a feasible way for trunk stabilization. Besides, research already indicated that in persons with musculoskeletal shoulder pain, a scapulothoracic posture retraining program results in reduced shoulder disability and pain, and ameliorated scapulothoracic movement and muscle activation patterns [18].

1.2 Wearable technologies for posture monitoring and correction

The aforementioned observations suggest the potential usefulness of posture monitoring and feedback technology addressing motor control for rehabilitation training. Technology-assisted training may offer advantages including more efficient training, the variation of training input, ease of use and low cost [11, 19]. Posture monitoring and correction technologies could monitor the user's abnormal posture and provide accurate feedback to encourage users actively adjust their posture [20], showing potential to support rehabilitation activities [11, 21]. In broad terms, there are five kinds of monitoring methods available: 1) traditional mechanical systems (e.g. goniometer); 2) optical motion recognition technologies [22]; 3) marker-less off body tracking systems like depth camera-based movement detection systems (e.g. Microsoft Kinect [23, 24]); 4) Robot-based solutions [25, 26]; 5) wearable sensor-based systems [27]. The present research is primarily concerned with the latter of these approaches. While optical solutions and off-body tracking systems are arguably more mature and reliable than wearable systems, they constrain training scenarios in several ways: optical motion trackers require a large space to operate successfully and suffer from potential occlusions. Higher-end infrastructure-based sensing systems such as the Vicon Tracker [22] (Vicon Motion Systems, Ltd., Oxford, UK) can be costly, are location bound and require substantial effort for their installation, which can hinder their wider availability and application. Recently, the miniaturization of devices and the evolution of sensing and body area network technologies [28, 29] have fueled an increasing emphasis on wearable rehabilitation technology, which may offer numerous advantages over traditional rehabilitation [30, 31], such as: low cost, flexible application, remote monitoring and comfort [29] . Towards the field of rehabilitation, wearable motion sensing systems have been classified into two main categories by Hadjidj [32]: a) movement classification including gait analysis and activity recognition; b) movement measurements for different body segments. This thesis focuses on the latter, specifically on re-training motor skills, as the main goal is to develop wearable technology that monitors a patient's motor control during the performed activities in the context of rehabilitation therapy.

In the context of upper extremities rehabilitation, there is particular interest in technologies that can reduce the requirements for direct involvement and supervision by health professionals. Wearable sensing technology can help patients acquire the awareness of their posture and correct it when necessary [33, 34]. For example, in stroke rehabilitation technology can support training through providing interactive exercises and even games, designed to help the patient practice tasks, to improve their strength and control [35, 36]. Wearable sensing systems open up the possibility of independent training (without continuous therapist supervision), the provision of feedback to the end-user as an active monitoring system, or even to enable tele-rehabilitation scenarios [37].

Wearable systems with this purpose may involve various components, a simplified list could be as follows: for sensing (sensors, wearable electronics, smart textiles [38]), for processing (system control units, data processing techniques, advanced algorithms for data extraction and decision making, wireless communication modules [21]), for providing feedback and interacting with the user (user interface software, interactive games[39]) and for remote service (cloud computing, big data and machine learning [40, 41]). Aiming to support motor control training, it would be valuable to explore how to contribute from the various aspects.

1.3 To design systems that are aesthetic, wearable, easy to use, motivating and accurate

Designing and developing wearable systems for posture correction lies at the crossroads of research fields of human-computer interaction [42] , electronic technologies [43], industrial design [44, 45] and rehabilitation.

Engineering research has striven to develop new and accurate sensing devices[46], novel algorithms [47, 48] and advanced materials to achieve high accuracy and reliability. For example, Lorussi et al. [49] proposed using piezoresistive strain sensitive textile to detect postures. Studies paid attention to technical validation of required accuracy and effectiveness.

Researchers from the Human-Computer Interaction (HCI) field also contributed to important studies that address responsive and interactive experience, enabling hands-free interaction that expands bodily motion [50]as input of interactive systems. Markopoulos et al. [35]applied the approach of user-centered design to develop a watch-like wearable device with screen feedback for stroke survivors. Luo et al. [51] presented an interactive virtual reality system with arm suit embedded IMU sensors. Alankus et al. [15] explored motion-based video games for stroke rehabilitation. Various motivating feedback mechanisms that are not limited to the application of posture-sensing have been explored, e.g. haptics [52, 53], sound [54], color-changing interface [55] and shape-changing interface [56].

While HCI researchers focus on the interaction design aspects, designing wearable systems also places high demands for intuitiveness and sophisticated physical interfaces from an industrial design perspective. Some studies focused on integrating ergonomics into wearable computer design [45]. Bhomer et al. presented how conductive yarns and regular yarns are being knitted as a normal cardigan [57] for supporting elderly people rehabilitation. Lucy Dunne [58] investigated the impact of garment style and fit variables on the performance of posture monitoring garments that applications for rehabilitation could draw lessons from.

Designing wearable rehabilitation technology combines considerations from different fields, which also means that posture tracking technology supporting rehabilitation needs to address some diverse requirements. Considering the context of rehabilitation, it is necessary to pay attention to the user needs of both patients and therapists. We focused on the requirements from three perspectives: functional requirements driven by the therapeutical purpose of the device, technical requirements for implementation, and requirements related to user experience. To be more specific, this research aims to study that intersection of the distinct research areas facilitating designing a wearable posture-sensing system to fulfill the requirements of being aesthetic, wearable, usable, motivating and accurate. We also aim for designing ready-to-apply systems that are simple and convenient to operate for end users, and we focus on the factors that may impact users' acceptance of wearable rehabilitation technology.

1.4 Interactive garments for upper-extremity rehabilitation

Wearable technologies benefit from multiple fields and recent advances have promoted the sensor miniaturization, smart textiles, computing technology and telecommunication for unobtrusive motion capturing [29]. Wearable systems are developing towards the second generation of wearables which has been described as Wearables 2.0 [59, 60]. Compared to Wearables 1.0 that considers wearables as accessories (e.g. wristbands, watches, etc.), Wearables 2.0 are emerging technologies that can be seen as everyday outfits with embedded sensors and processing modules, to provide high-level functions and service.

Electronic textile (E-textile) refers to a textile substrate that incorporates capabilities for sensing, communication and interconnection of sensors and other electronic modules with/within fabric [61]. We can distinguish three different degrees of integrating electronic components [62]: 1) Attached, where the textile functions as a container, e.g. an accelerometer attached on a vest [63] ; 2) Embedded, where electronic components are incorporated or embedded in the fabric, e.g. wired components by conductive yarns and textiles [64]; 3) Integrated, where technology is integrated into the fabric as an intrinsic part or where smart materials are knitted or woven into the garment's fabric, e.g., stretch-sensing fabric acting as a motion sensor [65]. The emergence of the latter two levels of integration has triggered a transformation of e-textiles, from passive substrates into active technological tools [66]. Currently, smart garments are developing rapidly with embedded or integrated sensing technologies that hold the promise of proper fit, comfort and unobtrusiveness.

Extrinsic feedback is important for rehabilitation training, for supporting the motor learning process and for sustaining motivation

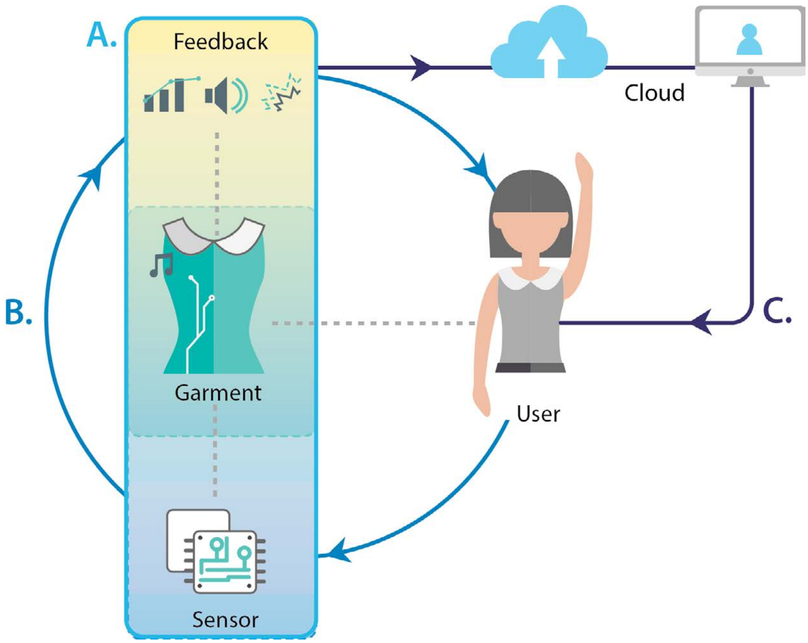


Figure 1.4 Architecture of interactive garment

during rehabilitation [11, 67]. Previous research [68] has suggested that extrinsic feedback may be useful for stroke survivors and may improve upper limb motor learning. One challenge while performing the long-term and repetitive motor control training exercise is the effective encouragement [51]. Ideally, feedback is given continuously for users with low proficiency levels, and with fading frequency schedules for more advanced users [11].

Figure 1.4 illustrates the general architecture of an interactive garment, consisting of three main building blocks: Part A mainly focuses on the implementation and technical feasibility of the garment, e.g. the solutions of integrating electronics into textile [66]. Part B focuses on the interaction with the user, e.g. how to collect data from the users [69] and how the feedback could encourage users [51]. Part C emphasizes the data services and data analyses techniques to enable tele-communication with therapists, for example Chen [59, 60], who proposed human-cloud integration based on smart clothing.

1.5 Research Objectives

While related research has been primarily concerned with developing wearable technology with the required accuracy and clinical validity of measurements, less attention has gone to integrating posture monitoring with training applications, to their usability and aesthetics, and to more general factors that are key to the eventual acceptance of this technology for patients, such as comfort, good wearability [70] and interactive feedback. The development of the *Zishi* garment reported in this thesis aims to address these considerations while exploring how *Zishi* could potentially help self-monitoring and correct the user's posture in a way analogous to how therapists monitor motor control of patients during traditional physical therapy training sessions.

This thesis attempts to answer the following central research questions:

RQ1: What's the current status of interactive wearable systems for upper body rehabilitation?

RQ2: How to design interactive posture monitoring garments to support rehabilitation?

RQ3: What should be considered when designing the system to support upper-extremity rehabilitation?

RQ4: To what extent can patients and therapists accept the interactive garment for rehabilitation?

RQ5: To what extent can the interactive garment support shoulder posture correction?

1.6 Research Approach

This research follows the approach of research-through-design [71] where the design practice is the medium in finding answers to the research questions and design activities as a part of doing research [72]. Zimmerman et al. [73] argue that it is an approach with the intention of generating new knowledge while based on designing, evaluating and reflection. Pieter Stappers and Elisa Giaccardi [72] sketch the field of research-through-design in a chapter in the second edition of "The Encyclopedia of Human-Computer Interaction". They argue that research-through-design differs from research-for-design as the latter refers to the focus on the design result [72]. While in research-through-design, the design and development of a prototype plays a central role in the generation of knowledge which could be communicated explicitly (text documentation as the carrier) or tacitly (prototype with framing as the carrier). In this thesis, we have applied the approach of research-through-design by iteratively making and evaluating the interactive garments, and this thesis presents the knowledge we acquired in the process. The evaluations are in the stage of pre-clinical evaluation including technical feasibility studies and usability studies, where we focused on designing systems that are aesthetic, wearable, usable, motivating and accurate.

Mackay et al. [74] proposed a triangulation framework that demonstrates how scientific and design disciplines in HCI can be integrated. This framework is a simple way to illustrate how diverse disciplines can contribute to a complex design research problem. We believe that their framework is a suitable way to map our research activities, for two reasons. Firstly, as our research topic was drawn from distant disciplines of rehabilitation, wearable technologies and industrial design, we need to communicate our work with other researchers and designers who are not in the mixed disciplines. Secondly, it is beneficial to illustrate interchange of the generated knowledge in the different research activities of design activities, theoretical and empirical studies.

Figure 1.5 is adapted from their framework and presents an overview of our performed activities in the PhD study and their relation to knowledge transfer. The theoretical activities consisted of an initial literature review [21], followed by a systematic survey (in Chapter 2)

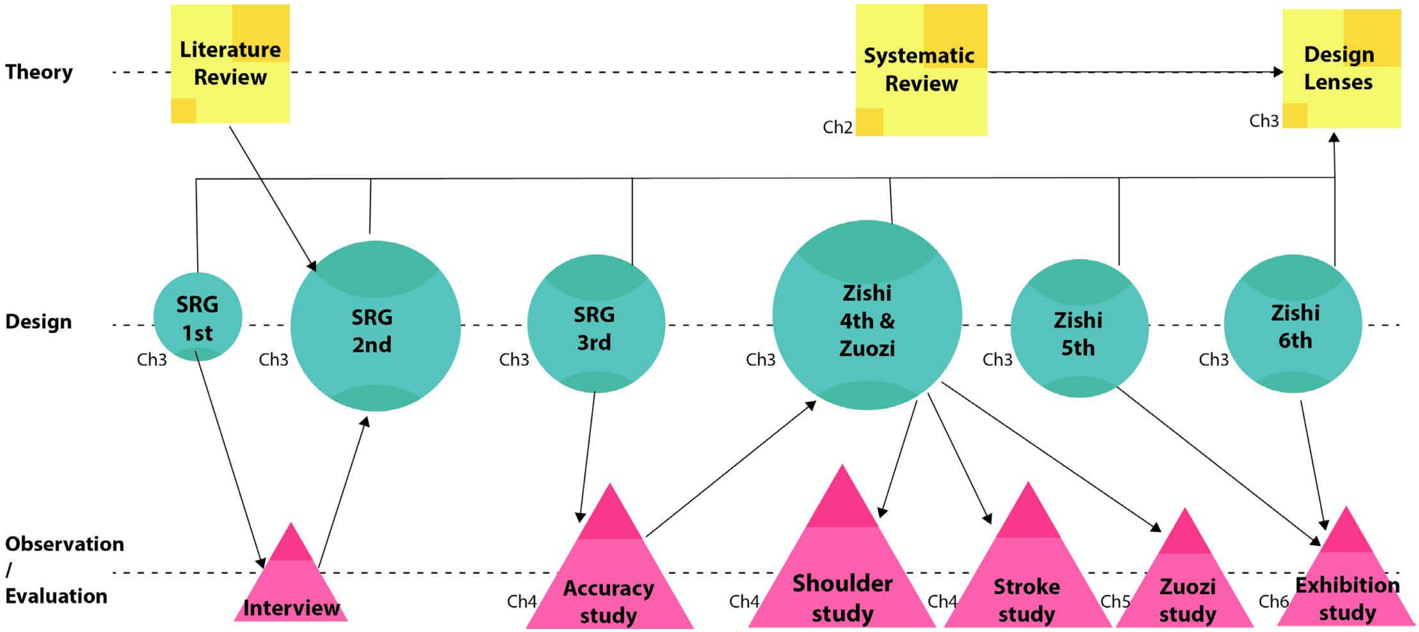


Figure 1.5 Overview of the activities performed in this thesis.

and the generated design lenses in six directions (in Chapter 3). The design activities include six iterations (in Chapter 3) of the interactive garment with earlier iterations named *Zishi* (the early iterations named Smart Rehabilitation Garment in related publications [64, 75, 76] and later iterations named *Zishi*). The empirical studies cover both methodical studies (e.g. accuracy study in Chapter 4 and the field study in Chapter 5) and informative studies (e.g. some reflections based on the user feedback in exhibitions). The figure also presents results from the literature review which inspired the prototype design and the question on how prototypes from different iterations deployed in the evaluations and contributed to the formulation of the design lenses.

A variety of research methods were employed in the above-mentioned activities:

a) In Chapter 2, we presented a systematic review study on interactive wearable systems for upper body rehabilitation. A systematic review is the type of literature review that provides an objective summary and critical analysis of current articles relevant to a research question. It is not a common research method in the HCI community whereas it is a typical method to summarize evidence for clinical studies and healthcare-oriented studies. We have followed the common stages summarized by Lindsay S. Uman [230] including 1) Formulate the review question; 2) Define inclusion and exclusion criteria; 3) Develop search strategy; 4) Select studies; 5) Extract data; 6) Assess study quality; 7) Analyze and interpret results and 8) Disseminate findings.

b) In Chapter 4, we applied the approach of experimental design including quantitative methods and qualitative methods [77]. In the accuracy comparison study and within-subject field study focused on sedentary work, we collected posture data from the users, analyzed and reported through significance tests. In the studies regarding users' attitudes, we applied multiple questionnaires (see Appendix I) concerning credibity, intrinsic motivation, technology acceptance and usability. Besides, semi-structured interviews and other descriptive investigations were also applied sporadically.

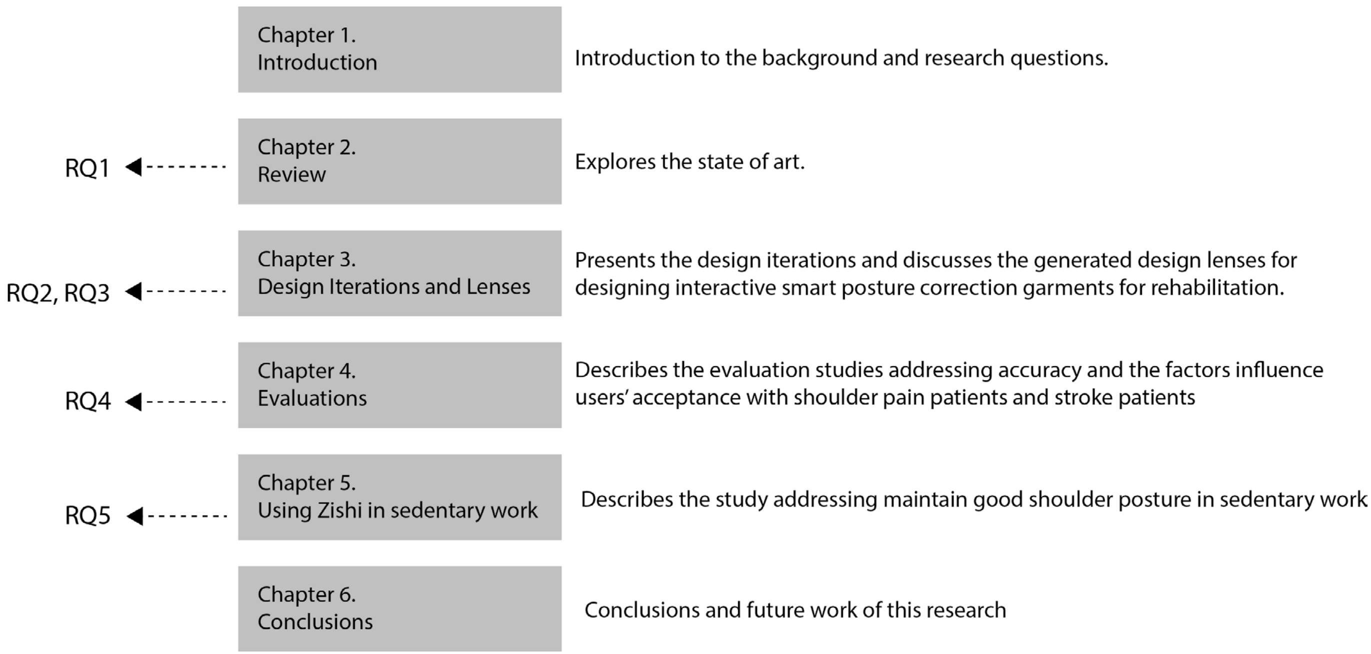


Figure 1.6 Thesis Outline

1.7 Thesis outline

Figure 1.6 shows the thesis outline and how the research questions have been answered by the chapters.

Chapter 2 is a systematic review that explores the state-of-art in the field of interactive wearable systems for upper body rehabilitation.

In Chapter 3, we first describe the development of a smart garment, which we call *Zishi*, to support trunk and scapulothoracic posture training by monitoring compensatory movement and synchronously providing feedback. We present the design iterations following an iterative design process. The chapter reports six design lenses of which designers could use the parameters while designing smart garments for rehabilitation.

Chapter 4 follows up on evaluation studies with different iterations. We present the output of *Zishi* compared to an Optical system in an accuracy evaluation. Then we outline how *Zishi* was used for motor control training and how *Zishi* was evaluated in terms of 'credibility and expectancy', 'usability', 'technology acceptance' and 'motivational' aspects with its users.

Chapter 5 describes the study about using *Zishi* in persons during sedentary work to explore how smart garments and supporting applications can help office workers to maintain a good posture, and guide them to carry out shoulder exercises at their workplace.

Finally, in Chapter 6 we present the summary of this thesis, statement of contributions, reflections on the methodology and future works of this research.

2

Interactive wearable systems for upper body rehabilitation: A systematic review.

This chapter is based on:

1. Q. Wang, P. Markopoulos, Y. Bin, W. Chen, A. Timmermans. Interactive wearable systems for upper body rehabilitation: A systematic review. J. Neuroeng. Rehabil. 2017, 14: 20.

My contribution is in conceiving the idea, carrying out the study selection, data extraction and manuscript drafting.

Abstract

Background

The development of interactive rehabilitation technologies which rely on wearable-sensing for upper body rehabilitation is attracting increasing research interest. This chapter reviews related research with the aim to: 1) To inventory and classify interactive wearable systems for movement and posture monitoring during upper body rehabilitation, regarding the sensing technology, system measurements and feedback conditions; 2) To gauge the wearability of the wearable systems; 3) To inventory the availability of clinical evidence supporting the effectiveness of related technologies.

Method

A systematic literature search was conducted in the following search engines: PubMed, ACM, Scopus and IEEE (January 2010-April 2016).

Results

Forty-five papers were included and discussed in a new cuboid taxonomy which consists of 3 dimensions: sensing technology, feedback modalities and system measurements. Wearable sensor systems were developed for persons in: 1) Neuro-rehabilitation: stroke (n=21), spinal cord injury (n=1), cerebral palsy (n=2), Alzheimer (n=1); 2) Musculoskeletal impairment: ligament rehabilitation (n=1), arthritis (n=1), frozen shoulder (n=1), bones trauma (n=1); 3) Others: chronic pulmonary obstructive disease (n=1), chronic pain rehabilitation (n=1) and other general rehabilitation (n=14). Accelerometers and inertial measurement units (IMU) are the most frequently used technologies (84% of the papers). They are mostly used in multiple sensor configurations to measure upper limb kinematics and/or trunk posture. Sensors are placed mostly on the trunk, upper arm, the forearm, the wrist, and the finger. Typically, sensors are attachable rather than embedded in wearable devices and garments; although studies that embed and integrate sensors are increasing in the last 4 years. 16 studies applied knowledge of result (KR) feedback, 14 studies applied knowledge of performance (KP) feedback and 15 studies applied both in various modalities. 16 studies have conducted their evaluation with patients and reported usability tests, while only three of them conducted clinical trials including one randomized clinical

trial.

Conclusions

This review has shown that wearable systems are used mostly for the monitoring and provision of feedback on posture and upper extremity movements in stroke rehabilitation. The results indicated that accelerometers and IMUs are the most frequently used sensors, in most cases attached to the body through ad hoc contraptions for the purpose of improving range of motion and movement performance during upper body rehabilitation. Systems featuring sensors embedded in wearable appliances or garments are only beginning to emerge. Similarly, clinical evaluations are scarce and are further studies needed to provide evidence on effectiveness and pave the path towards implementation in clinical settings.

2.1 Background

In musculoskeletal disorders, such as disorders of the neck-shoulder complex or osteoporosis, and in neurological disorders such as stroke, the integration of posture awareness of the upper trunk and shoulder complex as a stable basis for upper limb movement is an essential component of rehabilitation [78–80]. Therefore, feedback on the posture of the trunk and shoulder complex and feedback on upper limb movement may be supportive of motor learning [27]. Although the pathological mechanisms of posture deviation during static conditions (standing, sitting) or during movement performance (upper limb activities, posture during gait) are quite different across the above mentioned patient populations the corresponding therapeutic approaches share an emphasis on increasing patient awareness of correct posture and movement patterns and the provision of corrective feedback during functional task execution. In all of the above patients, intrinsic feedback mechanisms that inform the patient (e.g. proprioceptive cues) are impaired [67, 81, 82] and extrinsic feedback is advocated to relearn correct joint positions/posture during movement. Traditionally extrinsic feedback is provided by a therapist, so this way of learning is very time consuming and difficult to carry out independently, e.g. during home exercises. Suitable rehabilitation technologies can potentially play an instrumental role in extending training opportunities and improving training quality.

Posture monitoring technologies show great benefits of supporting rehabilitation activities [21, 27]. Generally, the five categories of methods for posture monitoring are: mechanical, optical motion recognition system [22], depth camera-based system [23, 24] , robot-based solutions [25, 26] and wearable sensor-based system [27]. A substantial number of wearable posture/motion monitoring systems for rehabilitation have been reported in literature in recent years [28–31], though very few have been used in clinical studies. Some studies introduce innovative wearable sensing technologies, e.g. Kortier et al. [83] developed a hand kinematics assessment glove based on attaching a flexible PCB structure on the finger that contains inertial and magnetic sensors. Tormene et al. [84] proposed monitoring trunk movements by applying a wearable conductive elastomer strain sensor. Studies like this are primarily concerned with demonstrating the accuracy and reliability of the technology they introduce. Another body of research concerns evaluations of existing rehabilitation technologies in terms of their validity. For example, Uswatte et al. [85] conducted a validation study of accelerometry for monitoring arm activity of stroke patients. Bailey et al. [86] proposed a study on a accelerometry-based methodology for the assessment of bilateral upper extremity activity. Lemmens et al. [87] report a proof of principle for recognizing complex upper extremity activities using body worn sensors.

There are a few examples of a literature that grows fast. The need arises to classify related works and identify promising trends or open challenges in order to guide future research. To address this need, there have been several reviews of research on wearable systems for rehabilitation, which take quite diverse perspectives on this vibrant field. An early review by Patel et al. [29] takes a very broad perspective that covers health and wellness, rehabilitation and even prevention, reviewing wearable and ambient technologies. Hadjidj et al. [32], provide a non-systematic review of literature on wireless sensor technologies focusing on technical requirements. Some studies focus on physical activity monitoring [88, 89] a technology domain that has had substantial growth and impact, but which is not specific to rehabilitation. Allet et al. [89] review wearable systems for monitoring mobility related activities in chronic diseases; this review covered mostly systems measuring general physical activity and found no works reaching the stage of clinical testing. Some studies provide an in-depth overview of movement measurement and analysis [90–92] technologies, though these are not necessarily integrated in rehabilitation systems and are usually still at the stage of proof of principle for a measurement technique. Vargas et al. [93] reviewed inertial sensors applied in human motion analysis, and concluded that inertial sensors can offer a task-specific accurate and reliable method for human motion studies. A couple of recent surveys [38, 94] have reviewed e-textile technologies applied in rehabilitation, though one of their main conclusions was to identify the distance separating the requirements for applying textiles to rehabilitation from the current state of the art. Also, they identify that the potential of providing feedback to patients based on textile sensing remains largely unexplored. Some studies concentrated specifically about how feedback influences therapy outcome [68, 95, 96], however the systems involved are not only wearable systems and all these reviews date 6 years or longer. Wang et al. [21] reviewed wearable posture monitoring technology studies from 2008 to 2013 for upper-extremity rehabilitation, yet unlike the present article, no systematic comparisons based on technology, system usability, feedback and clinical maturity were provided. In line with Fleury et al. [38] they found that only a few studies report the integration of wearable sensing in complete systems supporting feedback to patients, and very few of those have been tested by users with attention to the usability and wearability. Given the limited nature of that survey, such a conclusion was tentative calling for a systematic survey to gauge the state of the art in upper body rehabilitation technologies that integrate wearable sensors. The focus of the present survey is different regarding to the sensor type and placement, and rehabilitation objective. The present article contributes a different perspective to these surveys by critically reviewing and comparing systems comprising of feedback to support upper body rehabilitation with regard to their functionality and usability. In this review, we focus on interactive wearable systems that provide feedback to end-users for rehabilitation. In addition, in order to review the latest and most innovative technological solutions that shed a light on the state of the art wearable solutions for rehabilitation, only articles published later than 2010 are considered.

The translation from a technical tool towards a clinically usable system is not straightforward. Prerequisites for therapists and patients to use technology supported rehabilitation systems are the easy-to-use character of the system, its added value to their habitual rehabilitation programs and its credibility. Besides, it is of major importance to design the system feedback as this positively influences motivation and self-efficacy [11]. Advanced technologies provide increasing possible forms of feedback and a growing number of studies used interactive wearable systems to motivate patients in the intensive and repetitive training.

As such, the purpose of this review is to provide an overview of interactive wearable systems for upper body rehabilitation. In particular, we aim to classify from the following aspects:

1) To inventory and classify interactive wearable systems for movement and posture monitoring during upper body rehabilitation, regarding the sensing technology, system measurements and feedback conditions;

2) To gauge the wearability of the wearable systems;

3) To inventory the availability of clinical evidence supporting the effectiveness of related technologies.

2.2 Method

2.2.1 Literature search strategy

A literature search was conducted in the following four databases: PubMed, IEEE Xplore, ACM and Scopus. Papers addressing the following aspects were selected: rehabilitation, upper body, posture/motion monitoring, and wearable systems. MeSh (Medical Subject Heading) terms or Title/Abstract keywords and their synonyms and spelling variations were used in several combinations and modified for every database. Articles published from January 2010 to April 2016 were reviewed. The general search strategy including the used search terms are listed in Table 2.1. This search includes refereed journal papers and peer reviewed articles published in conference proceedings. Only English articles are included.

Table 2.1 Literature search strategy

Rehabilitation	“rehabilitation” OR “telerehabilitation” OR “motor activity” OR “physical therapy” OR “telemedicine” OR telemetry OR “motor learning”
	AND
Upper body	“upper body” OR “upper extremity” OR “spine” OR “back” OR “arm hand” OR “shoulder” OR “elbow” OR “wrist” OR “joint”
	AND
Posture / movement monitoring	(“monitor” OR “motion” OR “posture” OR “sensing” NOT “walking”) OR (“acceleromet*” OR “inertial sensor” OR “ sensor system” OR “sensor network” OR gyroscope OR MEMS OR IMU)
	AND
Wearable systems	wearable OR garment OR textiles OR wireless OR mobile OR “smart phone”

2.2.2 Study Selection Process

The article selection process consisted of following steps using the PRISMA [97] guidelines (see Figure 2.1) A computerized search strategy was performed for the period January 2010 until April 2016; 2) After removal of duplicates, two independent reviewers (QW and BY) screened titles and abstracts of the remaining articles; 3) The same 2 independent reviewers read the full texts and selected articles based on the inclusion/exclusion criteria. In cases where a journal paper covered the contents reported in the earlier conference publications, the journal paper was preferred over the conference paper. In cases where the overlap was only partial, multiple publications were used as sources, but only counted as one in our statistics and table entries. The consensus rates were 90.5 and 81% respectively during the first and second review rounds; disagreement was resolved by discussing reasons for exclusion. When authors had published several studies on same research initiative, only the most recent studies were retained. In cases of disagreement between the two reviewers, a third reviewer (WC/AT) decided whether the article should be included or not.

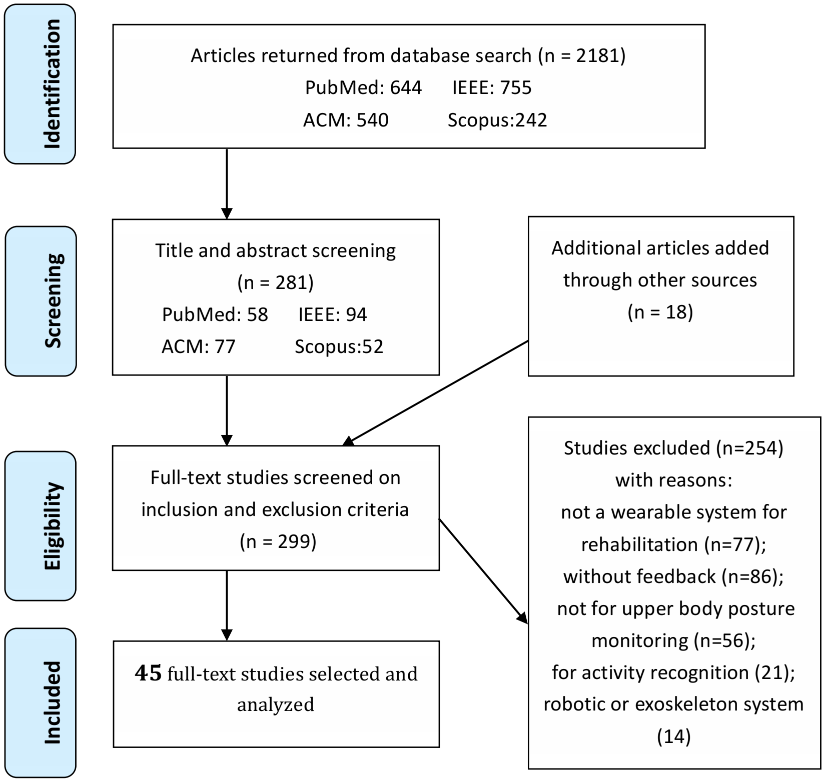


Figure 2.1 Prisma [97] flowchart of the results from the literature search.

Inclusion criteria:

a) The articles concern a wearable system.

b) The system is intended for rehabilitation purposes (in home and community settings).

c) The study includes upper body training (upper extremity, neck, spine).

d) The system described is a movement tracking or posture monitoring system

e) The wearable systems provide feedback to the end users of their training results or performance

g) Articles were published in the last 6 years

h) Articles were written in English

Exclusion criteria:

a) Prosthetics, coaching and information/educational systems

b) Activity recognition systems

c) Robotic system or exoskeleton

d) The study sticks adhesive sensors to human skin directly

e) Reviews

f) Books

2.2.3 Data extraction process

Two researchers (QW and BY) extracted data independently according to a predetermined template. The extracted data included the technology used, the sensor placement, the feedback, validation test level, the wearability of the system, and its purpose (patient category, posture or trunk rehabilitation). As for feedback, the researchers classified feedback according to the feedback modality (knowledge of results feedback/knowledge of performance feedback, concurrent/ terminal, vibrotactile/auditory/visual). With regard to the level of validation, it was noted whether the paper reports a technical performance evaluation, an empirical usability test, or a clinical trial to assess the effectiveness of the technology. In addition, this review follows the taxonomy of (WSN) for clinical rehabilitation applications proposed by Hadjidj et al. [32] in 2013.

2.3 Results

2.3.1 Database Search and paper lists

An overview of the results in the different stages of the article selection process is shown in Fig. 1. From the 2181 articles that were identified with the search strategies, 45 papers are included in this review after the selection process. The primary features of the surveyed systems are summarized and compared in Table 2.2.

Table 2.2: Summary of the paper lists and features (in the end of this chapter)

2.3.2 Taxonomy Structure

To better understand the emerging phenomenon and classify the systems, a new cuboid taxonomy (shown in Figure 2.2) has been proposed, which consists of 3 dimensions: sensing technology, feedback modalities and system measurements. Each dimension pertains to a group of different categories, and has no orientations. These dimensions are key principles for interactive wearable systems for upper body rehabilitation. One dimension is “sensing technology”, it inventories the involved advanced sensing techniques such as Acc/ IMU, Flexible angular sensor, E- textile and Others. “Feedback” is another dimension that is essential for interaction between the user and the wear- able systems. Feedback concerns different modalities, namely Visual, Auditory, Haptic and Multi-modal modalities. A third dimension is “measurement”. Every system provided different measurements of upper body kinematics which is the basis of building a suitable application for specific pathologies. In our taxonomy, “measurement” includes: Range of Motion, Amount of Use and Body Segment Posture. All the 45 articles have been positioned in the cuboid layers, and thereby the features of each system are clearly visualized. Some systems overlap multiple cells. Remarkably, most papers (n=28) are located at the overlap cells of using Accelerometers or IMU sensors and providing visual feedback. We will discuss more details in following sections.

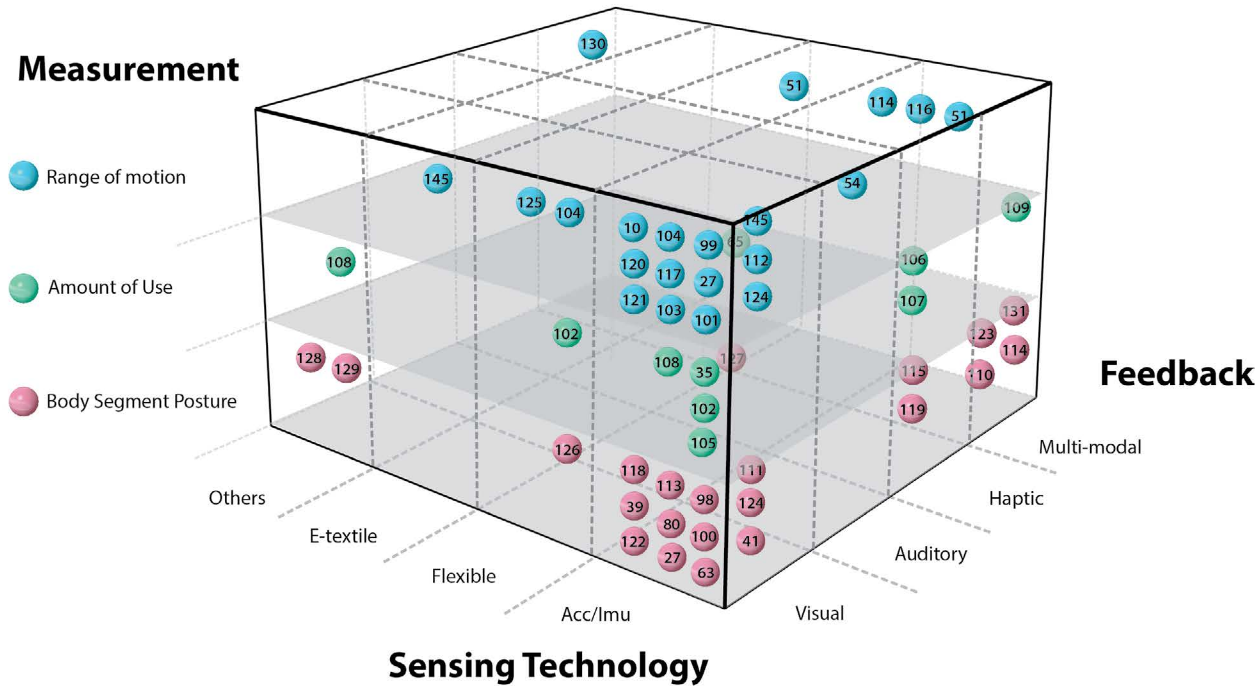


Figure2.2 Taxonomy of interactive wearable systems regarding sensing technology, system measurement and feedback modalities.

2.3.3 Status of Included Sensing Technologies

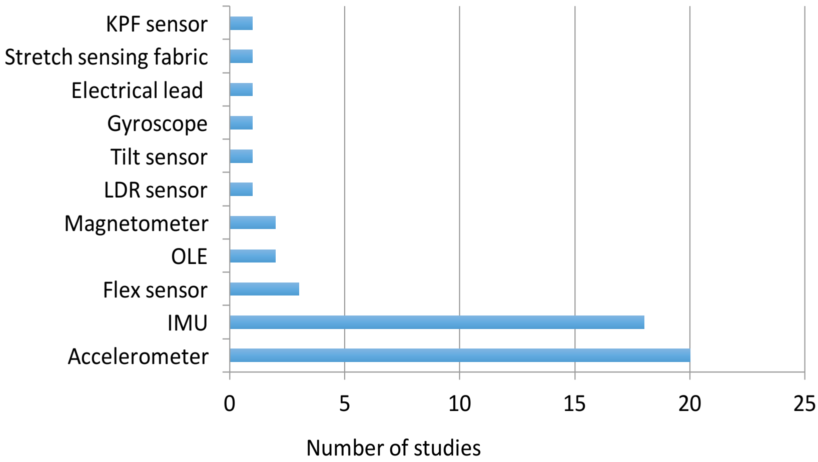


Figure 2.3 Sensing Technology Overview

Figure 2.3 summarizes the number of studies (horizontal axis) and the different technologies that are used (vertical axis). Some studies involved different technologies in their system. The involved sensing techniques could be classified into 4 categories:

1) Acc/IMU: accelerometer, gyroscope, inertial measurement unit (IMU);

2) Flexible angular sensor: flex sensor, optical linear encoder (OLE);

3) E-textiles: electrical lead, knitted piezoresistive fabric (KPF) sensor,

stretch sensing fabric;

4) Others: tilt sensor, magnetometer, light dependent resistor (LDR) sensor.

The accelerometer and IMU sensor are the most frequently used technology within the included feedback systems (used in 38 out of the 45 papers). An accelerometer measures proper acceleration, a gyroscope measures angular velocity, a magnetometer measures magnetic field, and an IMU uses a combination of these three. Systems based on accelerometer or IMU measurements normally consist of several sensor nodes, and can measure kinematic parameters such as orientation, position, velocity, as well as complex body posture and joint range of motion. Micro-electro-mechanical system (MEMS) technology has enabled the development of miniaturized inertial sensors [30].

In 20 studies [15, 35, 41, 63, 80, 98–101, 102–112] accelerometer(s) have been integrated: eight of them proposed a single-accelerometer-based system including the studies based on a smartphone built-in sensor, three studies proposed the fusion of an accelerometer with the gyroscope [100], optical linear encoder (OLE) module [104] and flex sensor [102] respectively, while other studies lean on accelerometer combinations.

Eighteen studies [10, 37, 39, 51, 54, 27, 113–124] applied IMUs in their systems, three [54, 116, 118]of them relied on a single sensor module. Most systems used 2–4 sensors, but studies that aimed for finger movement monitoring utilized more sensors [120, 121]. Hermanis et al. [122] proposed a novel system that may acquire data from up to 200 sensors, and have demonstrated a smart fabric which integrates 63 sensors in a wearable sensor grid architecture. Two studies [15, 39] used Wii remote as a sensing device and five studies utilized smartphone built-in sensors [41, 54, 112, 116, 118] supporting the growing trend for the use of smartphones for rehabilitation.

A flexible angular sensor includes a flex sensor and OLE strip. Deformation of the substrate of the flex sensor leads to a resistance output correlated to the bend radius. Ambar et al.[102] proposed a multi-sensor system with a flex sensor, force sensitive sensor and accelerometer. OLE consists of an infrared emitter and a receiver, which converts light information in to distance, the infrared light is reflected off the reflective code strip [104]. Flexible angular sensor arrays have been used on the finger for joint motion tracking. Luo et al. [51] located multi-point OLE strips on different finger segments while Saggio et al. [125] and Halic et al. [126] utilized flex sensors.

Three studies used e-textiles as sensors in their systems. Bhomer et al. [65] proposed a knitted garment based on stretch sensors made of conductive yarn. Klaassen et al. [37] applied “e-textile” goniometers based on knitted piezoresistive fabrics (KPFs), integrated KPF strain and KPF goniometers with IMU’s into a multi-modal sensing system. Friedman et al. [127] located six electrical leads on a glove, registering the electrical connection.

Besides, some researchers explored other metrics. Rahman et al. [119] and Salim et al.[128] proposed a glove-based motion detecting system by integrating LDR sensors and tilt sensors separately.

2.3.4 System Feedback

Feedback is important for rehabilitation training, for supporting the motor learning process in musculoskeletal and neurological pathologies [11, 95], and for sustaining motivation during rehabilitation [67].

Feedback Modalities

Table 2.3 classifies the different feedback modalities used in the included studies.

Table 2.3 Systems Feedback

Feedback Modality		Reference
Visual	Abstract (lines, curves, gauges, bars, or point.)	[27, 35, 98, 102, 103, 128][10, 37, 41, 105, 108, 112, 124]
	3D model of limb or human body or structure	[99–101, 104, 117, 120–122, 125]
	Game	[39, 63, 113, 118, 126, 129]
Haptic	Vibrotactile display	[106, 107, 115, 119]
Auditory	Musical pattern	[54]
Multi-modal		[51, 65, 80, 109–111, 114, 116, 123, 127, 130, 131]

Visual display is the most common (n=40) way to provide feedback. With visual feedback, the users learn a motor task by therapeutic intervention (training instruction that needs to be achieved) or from the patient him/ herself (to compare to the correct/desired movement). In many simple tasks, the task-relevant variable has been represented on a normal screen in a simple abstract form of lines and curves [41, 98, 102, 103, 105, 112], gauges [27, 108], bars [35, 128], or a combination for showing different parameters [10, 37, 124]. For feedback on simple task performance, a numeric or graphic display might be sufficient, since the small number of relevant variables can be meaningfully and directly represented with high information clarity. Besides simple abstract feedback, the global feedback [21]about the posture and position could be provided in a more natural way, which is classified as natural visualizations [132]. The 3D representation could be a virtual teacher/trainer [100, 101, 117, 130]or a 3D model of a limb/hand [99, 117, 120, 121, 125]. To provide quick and accurate feedback, some researches [104] have applied a simplified 3D mechanical model instead of a virtual human model to reduce the rendering time of the image. To motivate the users to practice or train longer, in several systems [39, 63, 113, 118, 129], the visual displays are incorporated into a training game for motor learning, 4 more studies [15, 51, 111, 127] also involved sound or haptic feedback in their games. Besides, some systems combine visual and other modalities as multimodal feedback systems [65, 109, 110, 114, 116, 123, 130]with the aim of enhancing learning effectiveness by reducing the cognitive load required for information processing.

In a study by Nguyen et al. [104], a virtual arm was driven by the subject to reach a virtual ball in the simulation environment, while the ball was controlled to move in a predefined route to guide both the real and virtual arm movements. Our results show that virtual reality has been commonly used within the included studies (three studies [51, 99, 130] in 2010, two [104, 113] in 2011, one [117] in 2013, three [39, 120, 129] in 2014 and one [121] in 2015). Further to using a computer screen as a visual feedback display, the emergence of smartphones is reflected on the number of the systems providing feedback on smartphones: 0 in 2010–2012, two [65, 116] in 2013, five [103, 108, 118, 126, 128] in 2014, four [41, 110, 111, 122] in 2015 and two [112, 123] in 2016.

Vibrotactile displays have been applied in wearable systems for giving information about navigation and directional information [115]. Luster et al. [107] use vibrotactile cues to provide positive reinforcement when performance goals are met during training practice in chronic stroke. The vibrotactile feedback can be located at specific points of interest, such as the forearm [115] or at C7 and T5 level of the spinal column [123], but may also cover a large limb area. Panchanathan et al. [119] developed a flexible vibrotactile strip that can be worn on the body for rich haptic communication. In addition, actuators' placement for vibrotactile feedback needs to be considered. For example, Ding et al. [130] mentioned the threshold distances for two vibrotactile actuators. These strips may be combined to create wearable two-dimensional haptic feedback. The capability of haptic feedback for presenting precise or complex information is limited, therefore they are often used in combination with visual/ audio feedback as a multi-modal feedback [109, 110, 123, 130].

Although only one study utilized auditory feedback as the exclusive feedback modality in their system [54], Newbold et al. [54] explored musically-informed movement sonification for stretching exercises, using stable sound to facilitate stretching exercises and unstable sound to avoid overdoing. Auditory feedback plays important role within the studies providing multi-modal feedback. For example, as a simple and clear notification of error or reward, e.g., as a beeping sound [123]. Furthermore, Bhomer et al. [65] proposed a more complex system in which the sound reflects the movement of the wearer as the pitch or volume of a tune is controlled by the stretch of a fabric sensor. Friedman et al. [127] encouraged the subject to hit notes with music feedback to practice hand function.

Feedback content and timing

Regarding to the content of feedback, most wearable systems present the skill outcome or goal achievement, defined as knowledge of results (KR) [133]. Examples are the summary feedback of the achieved number of specific training activities [35], movement parameter scores (range of motion, quality of movement)[27] , successful repetition number [41, 105, 113, 124]. Knowledge of performance informs about the movement characteristics that led to the performance outcome [133]. One common way is to present kinematic information such as position, time, velocity, and patterns [99, 100, 103, 104, 113]. Ding et al. [115] and Panchanathan et al. [119] proposed feedback on arm movement performance by vibrotactile feedback on directing towards the correct posture. Panchanathan et al. [119] also indicated the speed errors and how to correct them. Within the included studies, 16 studies applied KR feedback, 14 studies applied KP feedback and 16 studies applied both.

Eleven studies utilized game scenes to make repetitive movement more engaging for the patient and to motivate them to practice or train longer. Examples are grasping activities [39, 51], arm or finger movement performance [111, 118, 126, 127, 129], upper limb trajectory indication [113], and feedback based on compensatory movements within the games [15, 63, 80] .

Bandwidth feedback is defined as feedback given only when a movement error exceeds a certain threshold [132]. Bandwidth feedback is beneficial for personalized feedback to individual patients. Four papers [15, 63, 80] set compensatory movement limits as the trigger for game effects; another three studies used the reference position as a threshold [115, 123, 124] .

With regard to timing, feedback can be given during the training execution (concurrent feedback) or after completion of the training (terminal feedback) [132]. Concurrent feedback has been suggested to be effective for beginning users and terminal feedback may benefit more the skilled user [11]. Most included studies (n = 29) applied concurrent feedback strategies, 11 studies used both concurrent and terminal feedback, only 5 studies used terminal feedback, 4 of them by means of KR feedback and one study applied both.

2.3.5 Measurement

Wearable systems for the registration of body segment joint kinematics, give feedback on movements like flexion, extension, abduction, adduction, rotation and parameters such as time and speed. Hence the dimension “measurement” could be classified into: range of motion (movement distance around joint or body part), amount of Use (activity amount of body segment) and body segment posture (specific posture or body segment to target spatial location). Similar measurements may support various rehabilitation purposes and patient populations. Details of each study are presented in Table 2.

Measurement for different rehabilitation purposes

The included studies for upper body rehabilitation, had following aims: improve active joint range of motion, improve movement performance, improve movement coordination, improve posture, improve muscle strength, overcome learned non-use and improve performance of ADL (activities of daily living) skills.

Sixteen studies [10, 27, 37, 54, 99, 101, 103, 104, 112, 114, 116, 117, 120, 121, 124, 125] focused on the measurement of range of motion (ROM) with the common purpose of improving active joint range of motion. Studies by Timmermans et al. [27] and Parker et al. [10]also concentrated on improving ADL skills for Stroke. Harms et al. [125] aimed at improving posture and Newbold et al. [54] aimed at reducing pain during rehabilitation in chronic pain patients.

The "Amount of Use" is used in 8 studies [35, 65, 102, 105–109]. Two studies [35, 107]targeted at bilateral arm movement detection (use) to overcome learned non-use and 2 studies [35, 102] mentioned improving ADL skills. Jeong et al. [105], Myllymaa et al. [106], Bhomer et al. [65], Friedman et al. [108], and Holden et al. [109] intended to motivate the amount of exercise during general rehabilitation.

The category "Body Segment Posture" includes 24 studies [15, 27, 39, 41, 51, 63, 80, 98, 100, 110, 111, 113–115, 118, 119, 122–124, 126–130] about measurement of specific posture such as compensatory movement [13] and motion guidance. Most (16 out of 24) systems aimed for improving movement performance as these studies help users understand the desired motions and guide them through correct movement patterns, followed by 7 studies for improving posture, two for improving ADL skills and one for improving coordination [127].

Measurement for different target population

In addition, we inventoried the target population addressed by interactive wearable systems (Table 2.4). Three categories are identified: 1) Neuro-rehabilitation: stroke (n = 21), spinal cord injury (n = 1), cerebral palsy (n = 2), Alzheimer (n = 1); 2) Musculoskeletal impairment: ligament rehabilitation (n = 1), arthritis (n = 1), frozen shoulder (n = 1), bones trauma (n=1); 3) Others: chronic pulmonary obstructive disease (n=1), chronic pain rehabilitation (n=1) and other general rehabilitation (n=14).

Table 2.4: Classification based on target population

Target Population		Reference
Neuro-Rehabilitation	Stroke	[10, 27, 35, 37, 39, 51, 80, 102, 104, 107, 109, 113, 115, 118, 123–125, 127, 128, 130, 131]
	Spinal cord injury	[111]
	Cerebral palsy	[63, 129]
	Alzheimer	[65]
Musculoskeletal impairment	Ligament rehabilitation	[98]
	Arthritis rehabilitation	[121]
	Frozen shoulder rehabilitation	[41]
	Bones trauma	[122]
Others	COPD(chronic obstructive pulmonary disease)	[116]
	Chronic pain rehabilitation	[54]
	General rehabilitation (hand, elbow, shoulder, total upper extremity), no specific pathology	[99–101, 103, 105, 106, 108, 110, 112, 114, 117, 119, 120, 126]

2.3.6 System Wearability

Sensor placements

Figure 2.4 illustrates the sensor placement for all the studies included in this review with the intention of showing an overview of the sensing module distribution on the upper body. The papers of Hermanis et al. [122] and Bhomer et al.[65] have not been included in this figure,

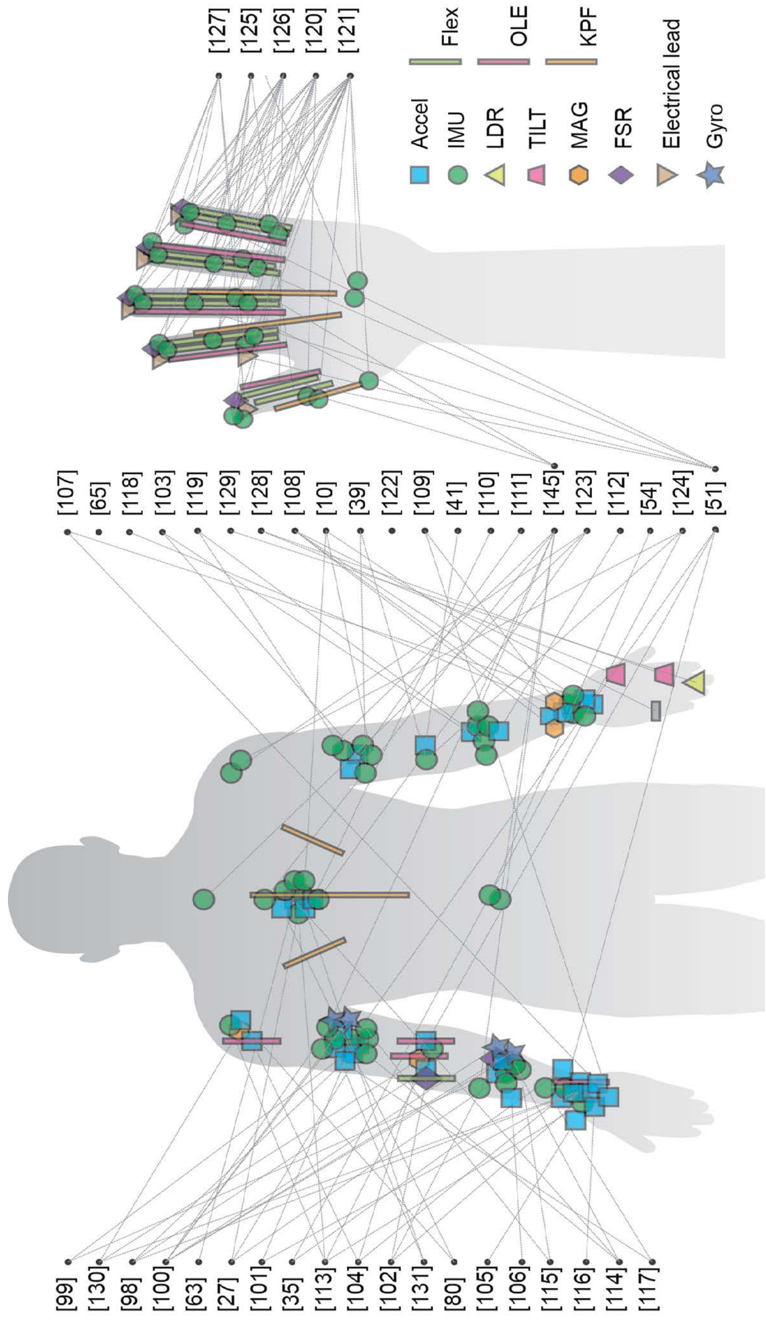


Figure 2.4 Infographic of Sensor Placements.

since the sensor grid system edcba [122] is capable of acquiring up to 63 sensors as a smart surface that can be worn on the back in the form of a blazer vest and the sensing areas knitted garment [65] based on smart textiles could cover the upper body instead of specific points. For the remaining articles, we have found that the main concentration of sensors is on upper arm (n= 16), forearm (n= 11), wrist (n= 14), elbow (n=9), trunk (n= 13 including location on chest and back) and finger (n=7).

Wearable design

Wearability has been defined by Gemperle et al. [134]as the interaction between the human body and wearable objects. Wearability is one of the key aspects for the acceptance of wearable systems; especially wearable systems that are aimed for long-term monitoring have high requirements for comfort.

From a system implementation perspective, the integration level of electronics and textile influences the wearability to a high extent. The integration level pertains to how electronic parts are embedded in a wearable system. Based on Seymour et al.[62], the integration level is distinguished into following categories: 1) Attachable, using a container like pocket or strapped with bands; 2) Embedded, sensing parts physically embedded into fabric, such as by conductive yarns; 3) Integrated, smart textiles sensors. In the second category, there are two ways to embed the sensing parts into the wearable system: with standard copper wires and with conductive yarns. Various ways of locating the sensors in the right places have been proposed. To be more specific, this review classified as follows: a) most included systems are in the stage of being attachable (n = 29) [10, 27, 35, 39,

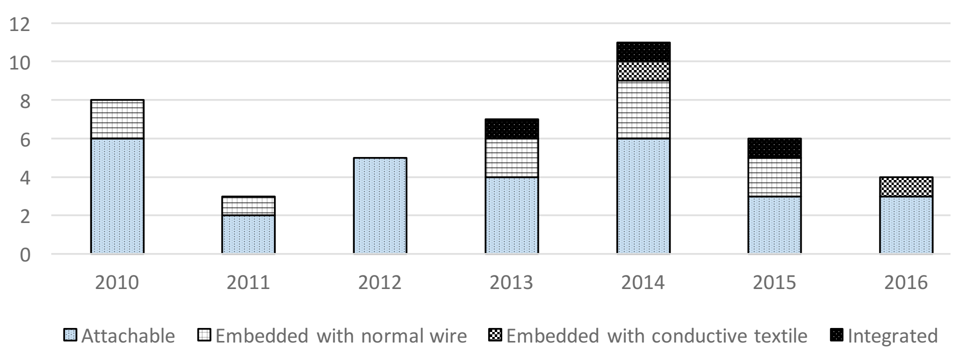


Figure 2.5 Overview of Integration classification.

41, 51, 54, 63, 80, 98–100, 102, 103, 105, 106, 108, 109, 111–116, 118, 124–126, 131], which is easy for prototyping and easy for operation of the system with a single device [63]; b) fewer studies are in the stage of embedded systems with normal wires(n = 10) [101, 104, 107, 110, 117, 120, 122, 128–130] ; c) for availability even fewer systems sensors are embedded in the fabric with conductive yarns (n = 2) [119, 123]; d) integrated into smart textiles (n = 3) [37, 65, 127]. Besides, O'flynn et al. [121] proposed a glove combined stretch- able substrate material and IMUs by customized PCB board doesn't require fabric platform.

Figure 2.5 summarizes the number of studies in different type of integration and in different years. Compared to systems in attachable level, embedded systems are more aesthetic and less bulky. Although the systems in integrated level with fabric-based sensing enhanced both comfort and aesthetics, the accuracy and flexibility supporting multi-DOF is limited [65, 121]. However with the emerging developments in smart textiles [37, 38], fabric-based sensing are showing great potential.

Wearable factors and requirements

Apart from system implementation issues, the efforts on improving the systems wearability can be classified in three levels: proposing a sensor package/platform design criteria/requirements [35, 114, 117, 123, 127]; including wearability related questions during the evaluation of the system with users [107]and, finally, reporting lessons learned about system wearability [105, 113, 119]. Table 2.5. summarizes claims made about wearability in these articles. Although the wearable systems are quite different, these quotes demonstrate current design requirements for wearability and how factors pertaining to wearability support these requirements. The relationship is illustrated in Figure 2.6.

Table 2.5: Quotes list about wearability requirements from included studies

Ref	Quotes from included studies
[104]	Q1. "does not restrain the human movement"; Q2. "without slipping on users' skin"; Q3. "be easy to wear"; Q4. "fit to human arms with different size";
[115]	Q5. "consideration of minimum critical distance for two adjacent vibrotactile actuators"
[114]	Q6. "unobtrusive and not limit the skin and muscle motion"; Q7. "place sensor on bones, ligaments and between muscles"; Q8. "with some flexibility in positioning"; Q9. "provide additional stability";
[117]	Q10. "must be non-invasive to be accepted by patient"; Q11. "have to avoid restraining the movements that the patient does in normal conditions";
[123]	Q12. "fit closely to body for higher accuracy"; Q13. "Easy to wear on and off"; Q14. "adjustable for different size"; Q15. "light, comfortable, appropriate for long term monitoring";
[107]	Q16. "how easy to put on/ take off the suit"; Q17. "how easy was it to move your affected arm compared to without wearing the wristband"; Q18. "how comfortable/lightweight were the wristbands";
[35]	Q19. "module size was too large, draw attention"
[119]	Q20. "reduce the quantity and bulk of the wiring"
[131]	Q21. "attach the harness around the neck, not the shoulders"; Q22. "stabilize the Wii Remote against the back to prevent rolling"; Q23."with a soft cloth cover to prevent rubbing against the skin";

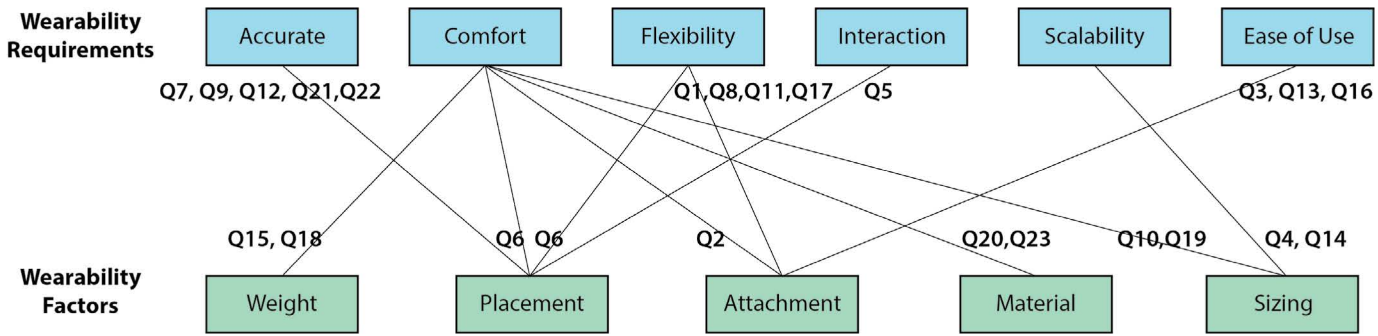


Figure 2.6 Wearability factors supporting wearable system requirements.

Based on Table 2.5 and Figure 2.6, following aspects has been concluded:

1. Acuracy: the wearable should help locate and keep the sensor in the right location on the body for high accuracy (Q7,9,10,19,20).

2. Comfort: wearable factors contribute both physiological comfort and psychological comfort (Q10,19); the system should be light (Q15,18), unobtrusive with suitable material (Q20,23) and attachment methods (Q2).

3. Flexible: the system should guarantee human movement flexibility (Q1,6,8,11,17).

4. Interactive: the wearable systems should support interactive therapy (Q5);

5. Scalable: the system should address body size diversity (Q4,14);

6. Ease of use: the system should be easy to operate and easy to put on and take off (Q3,13,16).

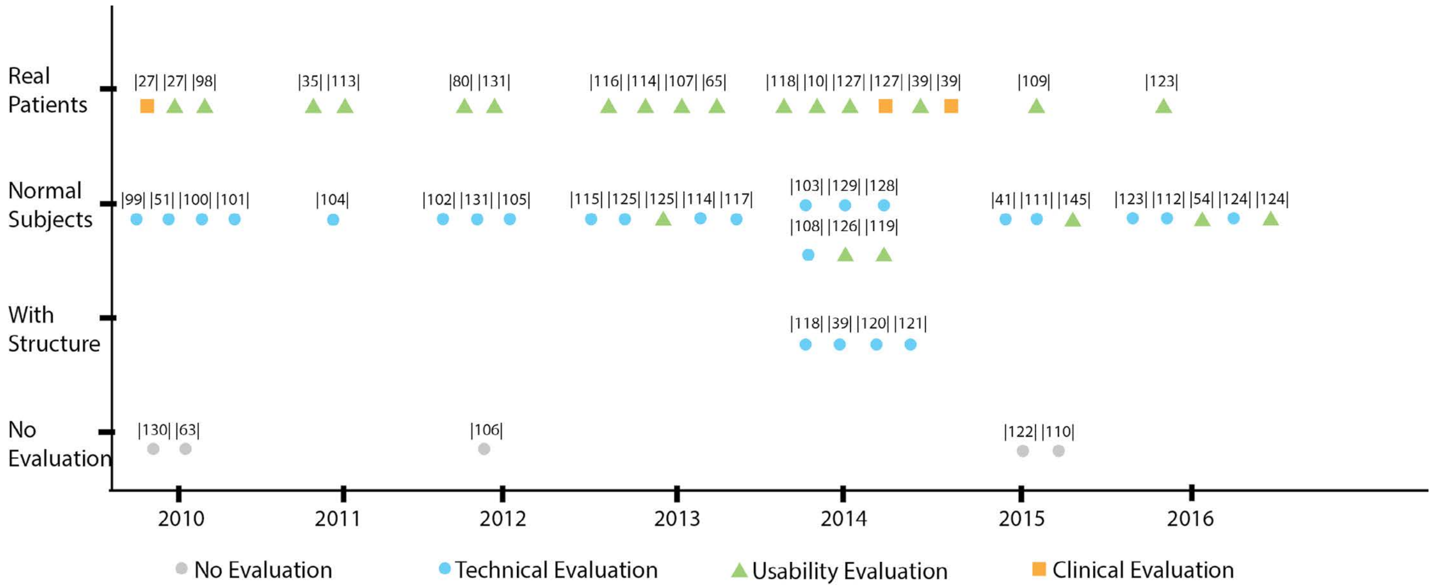


Figure 2.7 Systems Evaluation

2.3.7 Evaluation

The included systems are classified into four stages based on their evaluation status: a) no evaluation (n = 5); b) technical evaluation (n = 25); c) clinical trials (n = 3); d) usability test (n = 17), while six systems [114, 118, 123–125, 131] conducted both technical and usability evaluation in their studies and one study [39] conducted all. Some studies report evaluations from different perspectives. It is noteworthy that not all the experiments described in the studies could be defined as evaluation evidence. There are five studies that didn't provide evaluation evidence. Note that the avail- ability of "evaluation evidence" was not used as an inclusion criterion in this study, in order to not exclude reports on very novel systems that are presented as proof of concept/principle as, for example, the smart fabric embedded wearable sensor grid discussed above [122]. Figure 2.7 Illustrates the systems evaluation status in details.

The technical evaluation was conducted with regard to the following aspects: accuracy, sensitivity, reliability, power consumption and feasibility. There are 25 studies that describe a technical evaluation along such requirements, 21 studies didn't include patients and conducted the experiment only with healthy subjects.

Most sample sizes in the empirical evaluation studies reported are relatively small, ranging from 1 to 10, while only seven studies [54, 102, 105, 114, 119, 126, 127] involved more than 10 subjects, Halic et al. [126] conducted a usability evaluation with 46 subjects.

Although 16 of the included studies involved patients and reported usability tests, only three of these were clinical trials [27, 39, 127] including one randomized clinical trial [127] with 12 chronic stroke survivors for 2 weeks. From Figure 2.7, we can see that the usability evaluation with patients is drawing more attention from 2010 to 2014.

2.4 Discussion

This paper reviews the featured technologies developed over the recent 6 years, focusing on interactive systems of wearable-sensing based technology toward upper body rehabilitation. We proposed a taxonomy that consists of 3 dimensions: measurement, sensing technology and feedback. This new taxonomy may benefit other researchers to gain deeper understanding of the emerging projects, have more insights and explore the promising design space.

2.4.1 Discussion of wearable-sensing technologies

Advanced technologies have been developed and applied to solve the relevant application problems [90]. Various electronic sensors and systems have been applied in these studies, namely: accelerometer, gyroscope, inertial measurement unit (IMU), flex sensor, optical linear encoder (OLE), magnetometer, force sensitive sensor (FSRs), light dependent resistor (LDR sensor), tilt sensor, electrical lead, knitted piezoresistive fabric sensor (KPF) and stretch sensing fabric. The accelerometers and IMU's tend to be the most commonly used with the following advantages: they yield accurate essential values, are easy to use and are miniature in size.

Some new developments on innovative sensing technologies are noteworthy and promising though they have been excluded from the survey as they are only sensing technologies which do not support yet any user feedback: conductive thread based stretch sensors [135], a conductive elastomer sensor based system [84], stretchable carbon nanotube strain sensors [136] and soft nano-patches [137]. Based on the review study by Fleury et al. [38], the development of conductive elastomer sensors has primarily affected the recent advancements of textile- based motion sensing, providing comfortable garments with high integration level of electronic components and fabric. Although conductive elastomer based systems show accurate performance compared to IMU sensors, the single axis measurement and languid response limits their application for rehabilitation.

Besides, the sensing placement plays an important role for upper body rehabilitation as a combination of locations can provide the value of range of motion (ROM) assessment, body segment position, usage andposition. These values are crucial for rehabilitation therapy as their observation and interpretation influence how the treatment develops [138].

2.4.2 Discussion of systems feedback

It is important that feedback matches the proficiency level of the users [11]. The majority of systems (n=29) included in this review use concurrent feedback, which is mostly suitable for persons that are not proficient. Only 5 systems use terminal feedback and 4 of them by means of knowledge of results. There is a lack of systems that use fading frequency schedules that match the frequency of feedback provision to the progress of the patient: the more proficient the user, the less frequently feedback needs to be given so persons don't get dependent on the extrinsic feedback and learn to rely on their intrinsic feedback mechanisms [11]. This is a point of attention for future system developments.

Several feedback modalities were used. The natural visualization displays the movement of the user's body simultaneously with a virtual 3D modal. It could enhance the user's learning by imitation [139]. Also, users may enhance motor learning by mental practice, where similar brain areas are active than during overt motor actions [140].

Haptic and audio feedback do not require visual attention during the exercise. Haptic feedback, especially vibrotactile displays, are widely used (n = 8) in the systems included in the study. Haptic feedback allows patients to focus on specific body areas rather than divide their attention to a visual or auditory display. Vibrotactile feedback has been used to notify users on joint angle related errors and on speed of movement [119]. Vibrotactile feedback is also capable of presenting KP feedback [106, 115]. Auditory feedback as a substantial modality has been applied as an exclusive feedback by one study. Newbold et al. [54] explored musically-informed movement sonification. Bhomer et al. [65] and Friedman et al. [127] proposed systems in which the sound together with screen feedback reflects the movement of the wearer. Other studies applied auditory alarms as bandwidth feedback when a certain movement exceeds the threshold as an error notification [80, 103] or as notification for rewards [131].

Virtual reality technology has been used extensively in the included studies. Considering the recent booming development of VR technology and serious games, these technologies offer enormous potential for increasing the training intensity, engagement and social participation for patients.

Recent advances in smartphone technology such as their prevalence, ability to use anywhere, powerful processing ability and integration of sensor and display have had a major impact on their use in rehabilitation systems. Providing feedback like visual information on smartphones is common and effective, especially for the systems intended for remote monitoring.

2.4.3 Discussion of system wearability

Most articles have conducted a technical, a usability, and more rarely a clinical evaluation (only 3), while none of the included studies report a systematic wearability assessment, which is quite essential for user acceptance. Most included studies describe only superficially how to attach sensors on the human body, despite that the way this placement is done is very influential on both accuracy and comfort of the system.

Regarding the different sensing technologies and four integration levels of electronics and textiles, most studies in category Acc/IMU are restricted to the lowest level of integration where devices are attached to the body rather than integrated in a wearable system through ad hoc contraptions (e.g. Velcro strips), and sensors are distributed on body segments (e.g. upper arm, forearm and wrist) to work as a combination system. However, the studies within embedment level are increasing and have the advantages of stability, comfort, unobtrusiveness and feasibility. Studies in the category "Flexible angular sensor" are embedded sensors in a suitable platform and precisely located at body joint (e.g. elbow). Two studies in category "Others" embedded the sensor in gloves. Only three studies are in the integrated level based on smart textiles. However, applying smart textiles for posture detection, such as resistance changing materials, pressure-sensitive conductive sheets, knitted conductive textile and conductive yarns are growing trends in the area of wearable electronics that should soon be reflected in the domain of wearable rehabilitation technology [38, 141]. Currently, considering the rehabilitation context, "Acc/IMU" show superiority for projects with a high requirement of kinematic accuracy, while for a high preference of user experience the category "E-textile" has more advantages.

The reviewed studies have identified a number of requirements that may be key to improve wearability and usability of wearable rehabilitation technology: accuracy, comfort, interactiveness, flexibility, scalability, and ease of use. There has been little effort yet to evaluate wearability. In this respect, the study by Cancela et al. [70] is an inspiring example, where the Comfort Rating Scale was used to assess perceived exertion and physiological and biomechanical parameters were assessed to measure musculoskeletal loading.

2.4.4 Discussion of clinical validation

Only 3 systems have been clinically evaluated in clinical pilot trials [27, 39]and one randomized clinical trial [127] has been found. Compared to the results of the review study by Timmermans et al. [11], there have been only small improvements of the clinical evidence on wearable sensor-based systems. This can be attributed to the long time that technological developments require, and the fact that premature systems do not justify the time consuming and costly process of (randomized) clinical trials.

21 out of the 45 studies aim for stroke rehabilitation. The focus on stroke rehabilitation is in line with the general developments in the field of rehabilitation technology. However, it is surprising with regard to developments in wearable sensor systems for rehabilitation as they are mostly targeting a combination of posture monitoring in combination with upper extremity movement monitoring which is of great value for musculoskeletal as well as neurological pathologies. Compared to other wearable systems that support clinical applications for lower extremity rehabilitation and physical activity recognition, the clinical validation proportion of wearable-sensing systems for movement measurement during upper body rehabilitation shows disparity.

Clinical trials are important to assess the effectiveness of the systems with regard to the additional clinical value they may provide to the patients for improving their condition. Such trials are also paramount to pave the path towards implementation in clinical settings, as therapists will be hesitant to use them without clinical validation studies [19].

2.4.5 Inspirations from novel wearable concepts

Researchers working on wearables from the field of textile and fashion design and from the field of human computer interaction have been developing inspiring wearable solutions; although their objectives may not focus on rehabilitation, their work shows the future trend that can enhance wearable systems for rehabilitation:

- Textile displays as visual feedback. For example, textile display based on thermo-paint [142]. Based on the sensitive property of the thermos-paint, both concurrent feedback and long-term feedback (e.g. after one hour's training) could be provided. Or display technologies such as embedded mini LEDs or optical fibers can be embedded into clothing.

- New forms of haptic feedback, such as inflatable interfaces like the dynamic textile forms (e.g. origami textile structure [143]) that move.

- Personalized design and digital fabrication, adapting their form and functionality based on individual needs can be realized through 3D scanning and 3D printing techniques [144]. Customization design opens the opportunity of accurately and comfortable locating the sensors for individual patients.

2.5 Conclusions

Researchers from different backgrounds in biomedical science, engineering, computer science, and rehabilitation sciences have cooperated towards the development and evaluation of wearable systems for upper body rehabilitation. The results indicated that accelerometers and IMUs were most commonly used and they were used to monitor and provide feedback to patients on range of motion and movement performance during upper body rehabilitation. New possibilities are arising with up-coming technologies such as e-textiles and nano-sensors. Most systems were in the stage of feasibility prototypes, where only technical evaluations have been conducted. Some systems have reached the maturity to support user tests, while only three systems have been evaluated in clinical trials. There is a growing trend for using the smartphone as a monitoring device and as a feedback carrier. Rehabilitation training may be further improved when wearable sensing hardware takes enhanced wearability into account. Future research should focus on integrating advanced textile sensors, improving usability, wearability as well as clinical validation. The latter is of high importance to pave the path towards implementation into clinical practice.

Abbreviations

KR = Knowledge of results, KP = Knowledge of performance, ROM= Range of motion, FB = Feedback, FSRs = Force sensitive sensor, Accel = Accelerometer, IMU = Inertial measurement unit, OLE = Optical Linear Encoder, LDR sensor = Light Dependent Resistor, BW FB = Bandwidth Feedback, VR = Virtual Reality, ROM = Range of motion, Tech. = Technical evaluation, Usab. = Usability test, Clini. = Clinical trial, PC = Personal Computer.

Table 2.2: Summary of the paper lists and features

Reference	Technology (n)	Placement	Feedback			Evaluation		Wearability	Measurement &Rehabilitation Purpose	Target population
Lee et al. [99], 2010;	Accel (n=2)	Upper arm, Forearm	KP	Concurrent; Kinematic rendering of upper extremity.	VR	Tech.	Accuracy experiment on rotary stage and comparison experiment with goniometer (N=1)	Strapped with Velcro; Attachable;	ROM; Improve active joint range of motion;	General rehabilitation (arm) for for
Kapur et al. [130], 2010;	Magnetometer (n=3)	Wrist, Elbow, Clavicle	KP, KR	Concurrent; Kinematic rendering of upper extremity, for move Prescriptive KP FB;	VR; Vibrotactile FB	None	N/A	Full-body Suit; Embedded, normal wire;	Body Segment Posture; Improve movement performance;	Stroke
Luo et al.[51], 2010;	OLE(6), IMU (n=2)	Upper arm, Elbow, Wrist, Finger	KR	Concurrent; VR game based on Kinematic rendering of upper extremity and hand, Sound FB.	VR (game); Auditory FB	Tech.	Reliability Test (n=5);	Arm Suit & Glove; Attachable;	Body Segment Posture; Improve movement performance;	Stroke

Wang et al. [98], 2010;	Accel (up to 8),	Upper arm, Elbow, Wrist	KP, KR	Concurrent; Movement curve of each sensor node, Video of patient's training	Visual FB (PC, PDA)	Usab.	Pre-clinical evaluation trial on patients (n=2)	Strapped with Fabric bands; Attachable;	Speed & Body Segment Posture; Improve movement performance;	Ligament injury, Hemiplegic rehabilitation
Wai et al. [100], 2010;	IRIS mote (accel & gyro)	Upper arm, Forearm	KP,	Concurrent; Kinematic rendering of body, Sensor Reading.	Visual FB (PC)	Tech.	Accuracy measurement on subject	Based on straps; Attachable;	Body Segment Posture; Improve movement performance;	General rehabilitation
Dunne et al.[63], 2010;	Accel(n=1)	Chest	KR	Concurrent; Game score based on trunk posture, BW FB on trunk compensatory movement.	Visual FB (Multi-Touch Display, game)	None	N/A	Portable device, Attachable;	Body Segment Posture; Improve posture and movement performance;	Cerebral palsy children
Timmermans et al. [27], 2010;	IMU (n=3)	Chest, Upper arm, Forearm	KR KP,	Concurrent & Terminal; Gauge represents real-time joint angle, Avatar animation of upper body, Movement parameters score, etc.;	Visual FB (PC)	Usab. Clini.	Clinical evaluation (n =9)	Garment on torso & Strap on arm; Attachable;	ROM & Body Segment Posture; Improve active joint range of motion; Improve performance of ADL skills.	Stroke

Harms et al. [101], 2010;	Accel (n=2)	Forearm, Upper arm	KP	Concurrent; Avatar animation of upper body;	Visual FB	Tech.	Accuracy test on normal people (n=5)	Embedded into a wearable garment; Embedded;	ROM; Improve posture; Improve active joint range of motion;	General Rehabilitation (Shoulder and Elbow)
Markopoulos et al. [35], 2011;	Accel (n=2)	Wrist	KR	Terminal; Summary FB of arm use;	Visual FB (Watch-like device)	Usab.	Preclinical & Usability Test on real patients (n= 9)	Watch-like device; Attachable;	Amount of Use; Overcome learned non-use;	Stroke
Moya et al.[113], 2011;	IMU (n=4)	Back, Shoulder, Elbow, Wrist	KP KR	Concurrent; Avatar animation of body and arm movement, Sphere animation for trajectory indication, Repetition number, progress bar; Prescriptive;	VR (game)	Usab.	Preclinical & Usability Test (n= 23 therapists)	Special garment fixes sensor with Velcro; Attachable;	Body Segment Posture; Improve movement performance;	Stroke
Nguyen et al. [104], 2011;	OLE, Accel	Shoulder, Elbow, Wrist	KP	Concurrent; Kinematic model of upper arm and forearm; Prescriptive KP;	VR	Tech.	Comparison experiments for accuracy and performance (n=3); Repeatability and Reliability test (n= 5)	Fabric sensor package with Velcro strap; Embedded;	ROM; Improve active joint range of motion;	Stroke

Ambar et al. [102], 2012;	Flex sensor, Accel	Elbow, Forearm, Wrist	KR	Terminal; The number of the arm bent movement;	Visual FB (LCD)	Tech.	1, sensor performance report; 2, Comparison Experiment of FSRs and EMG; 3, ACC measurement activity.	Strapped with Velcro; Attachable;	Amount of Use; Improve performance of ADL skills.	Stroke
Alankus et al. [131], 2012;	Accel (Wii built-in, n=2)	Back, Upper arm	KR	Concurrent; Game result based on both trunk and arm movement; BW FB for trunk and arm compensatory movement;	Screen Visual FB (PC game); Auditory FB	Tech. Usab.	Validation Test on normal people(n=2); Preclinical & Usability Test on patients (n= 11)	Harness with straps around the neck, armband; Attachable;	Body Segment Posture; Improve posture and movement performance;	Stroke
Delbressine et al.[80], 2012;	Accel (n=2)	Back, Shoulder	KR	Concurrent; BW FB on trunk or shoulder compensatory movement with vibration;	Visual FB (Touchscreen)	Usab.	Preclinical & Usability Test on patients (n= 7)	Vest; Attachable; pocket	Body Segment Posture; Improve posture; Improve performance of ADL;	Stroke
Jeong et al. [105], 2012;	Accel (n=1)	Wrist	KR	Concurrent & Terminal; Speed, count, time of cycling movement;	Visual FB (PC)	Tech.	Accuracy test on normal people (n=7)	Strapped with Velcro; Attachable;	Amount of Use & Speed; Encourage arm hand use; Motivate exercise performance;	General Rehabilitation (arm)

Myllymaa et al. [106], 2012;	Accel (n=1)	Arm	KP	Concurrent; Motion instruction; Prescriptive KP FB;	Vibrotactile FB,	None	N/A	Strapped with band; Attachable;	Amount of Use; Improve muscle strength;	General Rehabilitation (arm)
Ding et al. [115], 2013;	IMU (n=2)	Forearm, Upper arm	KP, KR	Concurrent; Indication of movement direction for upper extremity; BW FB for the reference position; Prescriptive KP FB;	Vibrotactile FB	Tech.	Accuracy test on subjects (n=5)	Strapped with Velcro; Attachable;	Body Segment Posture; Improve posture and movement performance;	Stroke
Saggio et al. [125], 2013;	Flex sensor (n=5)	Finger, Palm	KP	Concurrent; Hand avatar;	Visual FB (PC)	Tech. Usab.	Repeatability and reliability test on normal people (n=6); Usability test on normal people (n=6)	Glove; Attachable;	ROM; Improve active joint range of motion;	General Rehabilitation (hand)
Spina et al. [116], 2013;	IMU (Smartphone built in)	Limb segment	KR, KP	Concurrent & Terminal; Teach mode and Train mode; Error notification, repetition number, motion speed; Prescriptive KP;	Visual FB (Smartphone); Auditory FB	Usab.	Usability test on normal people (n=4) and patients (n=7)	Strapped with holster; Attachable;	ROM; Improve active joint range of motion;	COPD(Chronic pulmonary obstructive disease rehabilitation)

Bleser et al.[114], 2013;	IMU (up to 10)	Chest, Upper arm, Forearm, Pelvis	KR KP	Concurrent & Terminal; Movement Error notification and correction FB; Training time, repetition number, progress bar; Descriptive;	Visual FB (Television screen); Auditory FB	Tech. Usab.	Technical evaluation based on therapy ground truth (n=7) Clinical evaluation focusing on usability and acceptance on patients (n=30)	Based on Velcro straps and elastic silicon; Attachable;	ROM & Body Segment Posture; Improve active joint range of motion; Improve movement performance;	General Rehabilitation;
Daponte et al. [117], 2013;	IMU (>2)	Limb segment (Upper arm, Forearm)	KP	Concurrent; Avatar animation of arm movement, Real-time joint angle & ROM value;	VR	Tech.	Function validation test (n=1)	Velcro based Sleevelet units; Embedded;	ROM; Improve active joint range of motion;	General Rehabilitation;
Luster et al. [107], 2013;	Accel (n=2),	Wrist	KR	Concurrent; BW FB on impaired arm use;	Vibrotactile FB,	Usab.	Usability test of vibration Feedback, Stroke patients (n = 4)	Wristband; Embedded;	Amount of Use; Overcome learned non-use;	Stroke
Bhomer et al. [65], 2013;	Stretch sensing fabric	Arm, low back	KP	Concurrent; Sound FB matched the arm and low back movement, Movement region indication;	Visual FB (Smartphone); Auditory FB	Usab.	Usability test with therapist and patients	Knitted garment; Integrated;	Amount of Use; Encourage arm hand use;	Alzheimer

Friedman et al.[127], 2014;	Electrical lead (n=6)	Finger	KR	Concurrent; Game result based on finger pinch and grasp motion;	Screen Visual FB (PC game); Auditory FB	Usab. Randomized Clic.	Usability test with storke patients (n=10) Randomized clinical trial with stroke patients (n=12).	Glove; Integrated;	Body Segment Posture; Improve coordination; Improve performance of ADL skills.	Stroke
Ferreira et al. [118], 2014;	IMU (Smartphone built-in)	Wrist	KR	Concurrent; Game results on arm movement performance;	Visual FB (Smartphone game)	Tech. Usab.	Accuracy measurement on structure, Usability of the system on patients (n=1)	Wristband; Attachable;	Body Segment Posture; Improve movement performance;	Stroke
Fortino et al. [103], 2014;	Accel (n=2)	Upper arm, Elbow	KP, KR	Concurrent & Terminal; Kinematic rendering of limb bending movement performance, Improvement index data; Descriptive;	Visual FB (Smartphone)	Tech.	Estimation accuracy on normal subject (n=1)	Elastic bracelets; Attachable;	ROM; Improve active joint range of motion;	General Rehabilitation (arm)

Panchanathan et al. [119], 2014;	IMU (n>1)	Upper arm, Forearm	KP	Concurrent; Vibration instruction for position and speed error;	Vibrotactile FB	Usab.	Usability test with normal people (n=16)	Sleeve; Embedded; Conductive ribbon	Body Segment Posture & Speed; Improve movement performance;	General Rehabilitation (arm)
Rahman et al. [129], 2014 ;	LDR sensor		KR	Terminal; Game score on arm movement;	VR (game)	Tech.	Accuracy and sensitivity test on normal people (n=2)	Fabric Glove; Embedded; Normal wire	Body Segment Posture; Improve movement performance;	Cerebral Palsy
Salim et al. [128], 2014;	Tilt sensor (n=2)	Hand	KP	Concurrent; Indication of arm movement direction;	Visual FB (Smartphone)	Tech.	Pilot experiment (n=1)	Fabric Glove; Embedded; Normal wire	Body Segment Posture; Improve movement performance;	Stroke
Friedman et al. [108], 2014;	Magnetometer(n=2), Accel (n=1)	Wrist, finger	KP	Concurrent; Amount of use of wrist and finger;	Visual FB (Tablet)	Tech.	Accuracy test on normal peoplev (n = 7)	Watch-like device, ring; Attachable;	Amount of Use; Encourage arm hand use; Motivate exercise performance;	General Rehabilitation (hand)

Parker et al. [10], 2014;	IMU (n=3)	Chest, Upper arm, Wrist	KP, KR	Concurrent & Terminal; Characteristics and results of performance by avatar presentation and charts; Prescriptive;	Visual FB (PC)	Usab.	Home-based on usability test on real patients (n=5)	Garment on torso & Strap on arm; Attachable;	ROM; Improve active joint range of motion; Improve performance of ADL skills;	Stroke
Halic et al. [126], 2014;	Flex sensor (n=5),	Finger	KP, KR	Concurrent; Avatar presentation, Game score;	Visual Game (Smartphone)	Usab.	Usability test with normal people (n=46)	Glove; Attachable;	Body Segment Posture; Improve movement performance;	General Rehabilitation (hand and wrist)
Tsekleves et al. [39], 2014;	IMU (Wii plus built-in, n=2)	Upper arm, Forearm	KR, KP	Concurrent & Terminal; Avatar presentation, game score, ROM value;	VR (game)	Tech. Usab. Clic.	Accuracy test on structure; Usability test with stroke patients (n=3); Small Clinical trial (n=1)	Based on strips; Attachable;	ROM, Body Segment Posture; Improve active joint range of motion; Improve movement performance;	Stroke
Moreira et al. [120], 2014;	IMU (n=11)	Finger, Palm	KP	3d hand model animation,	VR	Tech.	Accuracy test with structure; Reliability evaluation on normal people (n=1);	Glove; Embedded;	ROM; Improve active joint range of motion;	General Rehabilitation (hand)

O'Flynn et al. [121], 2015;	IMU (n=16)	Finger, Palm	KR, KP	Concurrent & Terminal; Movement error summary; 3d hand model animation, dynamic movement value & analysis;	VR	Tech.	Comparison accuracy test on structure.	N/A	ROM; Improve active joint range of motion;	Arthritis Rehabilitation
Hermanis et al. [122], 2015;	IMU (up to 200)	Back	KP	Concurrent; 3D rendering surface showing the current posture of back or limb;	Visual FB (Smartphone, Tablet or PC)	None	N/A	Sensing fabric based on sensor grids; Embedded; normal wire	Body Segment Posture; Improve posture;	Bones trauma or General Rehabilitation
Holden et al. [109], 2015	Accel (n=2)	Wrist	KR	Concurrent & Terminal; Training notification;	Visual FB (Watch-like device); Vibrotactile FB;	Usab.	Usability test on patients (n=7)	Watch-like device; Attachable;	Amount of Use; Encourage arm hand use;	Stroke
Ongvisatepaiboon et al. [41], 2015;	Accel (Smartphone built-in)	Elbow	KP, KR	Concurrent & Terminal; Shoulder joint angle value, repetition number;	Visual FB (Smartphone)	Tech.	Accuracy test on normal people (n=1)	Armband; Attachable	Body Segment Posture; Improve movement performance;	Frozen shoulder rehabilitation

Lee et al. [110], 2015;	Accel (n=1)	Back	KR	Concurrent; BW FB of unbalance error;	Visual FB (Smartphone); Vibrotactile FB	None	N/A	Based on strips; Embedded, normal wire	Body Segment Posture; Improve posture;	General Rehabilitation
Rahman et al. [111], 2015;	Accel (n=1)	Upper arm	KR	Concurrent; Successful repetition number;	Visual FB (Smartphone Game)	Tech.	Accuracy test on normal people (n=5)	Based on strips; Attachable	Body Segment Posture; Improve movement performance;	Spinal cord injury
Klaassen et al. [145], 2015;	IMU (n=8), KPF strain (n=2), KPF goniometer,	Chest, Upper arm, Forearm, Spine, Hand	KR, KP	Terminal; Range of motion value of body segments; Reaching performance; 3D full body reconstruction;	Visual FB;	Usab.	Usability test on normal people.	Shirt and glove; Integrated; Embedded;	ROM; Improve active joint range of motion;	Stroke
Wang et al. [123], 2016;	IMU (n=3)	Back, Shoulder	KR	Concurrent; Torso and shoulder movement value; BW FB on compensatory movement of torso or shoulder;	Visual FB (Smartphone); Vibrotactile FB; Auditory FB	Tech. Usab.	Accuracy test on normal people (n=7) Usability test on patients (n=8)	Embedded into a wearable garment; Embedded; conductive yarn	Body Segment Posture; Improve posture and movement performance;	Stroke, shoulder pain

Bittel et al. [112], 2016;	Accel (Smart-phone built-in)	Arm	KP	Concurrent & Terminal; Angular move-ment error;	Visual FB (Smart-phone)	Tech.	Accuracy and precision test (Comparison experiment with Biodex isokinetic dynamometer)	N/A; Attachable	ROM; Improve active joint range of motion;	General Rehabili-tation
Newbold et al. [54], 2016;	IMU (Smart-phone built-in)	Low back	KP	Concurrent; Sinification based on stretch for-ward movement;	Auditory FB	Usab.	Usability test on normal people (n=21);	Strapped with band; Attachable;	ROM; Improve active joint range of motion; Reduce pain;	Chronic pain reha-bilitation
Ploderer et al. [124], 2016;	IMU(n=3)	Shoulder, Elbow, Wrist	KP, KR	Terminal; Movement quality, joint ROM value and arm move-ment heat map; Exercise time and movements number;	Visual FB (PC)	Tech. Usab.	Accuracy test on normal peo-ple(n=1); Usability test on therapists (n=8)	Based on Velcro straps; Attachable;	ROM & Body Seg-ment Posture; Improve active joint range of motion; Improve posture and movement performance;	Stroke

3

Zishi: Design Iterations of Zishi and Design Lenses for Interactive Posture Monitoring Garments for Rehabilitation

This chapter is based on:

1. Q. Wang, P. Markopoulos, W Chen, "Smart rehabilitation garment design for arm-hand training" in Proceedings of the 8th International Conference on Pervasive Computing Technologies for Healthcare, PervasiveHealth '14, German,2014, DOI: 10.4108/icst.pervasivehealth.2014.255256;

2. Q. Wang, W. Chen, P. Markopoulos, "Smart Garment Design for Rehabilitation" in ICTs for Improving Patients Rehabilitation Research Techniques, Communications in Computer and Information Science, Vol. 515, pp 260-269.ISBN: 978-3-662-48645-0,2015;

3. Q. Wang, W. Chen, A. Timmermans, C. Karachristos, J.B. Martens, P. Markopoulos, "Smart Rehabilitation Garment for Posture Monitoring" in 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Milan,2015, DOI: 10.1109/EMBC.2015.7319695;

4. Q. Wang, "Designing Posture Monitoring Garments to Support Rehabilitation", In Proc. International conference on Tangible, Embedded and Embodied Interaction (TEI), Eindhoven, the Netherlands, 2016, DOI: 10.1145/2839462.285410;

5.Q. Wang, M. Toeters, W. Chen, A. Timmermans, P. Markopoulos, "Zishi: a smart garment for posture monitoring", In Proc. Of the 34th Annual ACM Conference on Human Factors in Computing Systems (CHI'16), San Jose, CA, USA, 2016, DOI: 10.1145/2851581.2890262;

My contributions to these papers are in the conception, prototype (garment and app) design and development, implementation and execution of the evaluation of Zishi, as well as in writing the paper.

3.1 Introduction

In Chapter 2 we have reviewed the state of the art in interactive garments for rehabilitation. We saw how research interest into wearable posture and motion monitoring systems for rehabilitation has grown rapidly in recent years [34]. Continuous posture monitoring and correction technologies providing accurate, real-time and reliable tracking and have a great potential to support several patient groups (neurological rehabilitation and chronic diseases). Many studies have been published focusing on novel technologies with high accuracy, reliability and validity evaluation of wearable devices [32], while it is important to design the system feedback as this positively influences motivation and self-efficacy [11, 27]. A variety of possible forms of feedback have been explored, and growing attention is paid towards designing interactivity in wearable systems to motivate patients in the intensive and repetitive training [10, 34].

There have been quite a few studies, which examine upper body posture monitoring systems using interactive wearable sensor technologies. However, in the previous chapter, we found only six studies out of the 45 articles on the topic of wearable-sensing based interactive systems concentrated on monitoring compensatory movements, while most systems located sensors on limb segments or joints for the measurements of range of motion, amount of use or other body segments position. These studies are reviewed briefly below.

Dunne et al. [63] proposed an interactive system for upper extremity rehabilitation in children with cerebral palsy which monitors trunk movements using accelerometers providing feedback through games played on a multi-touch display. Alankus et al. [15] concentrated on reducing trunk compensatory movement based on Wii remote and video games during training in stroke rehabilitation. Ploderer et al. [124] proposed a system named “ArmSleeve”, supporting occupational therapists in stroke rehabilitation, involving exercise and activities addressing the control of compensatory movement. Lorussi et al. [146] integrated a scapular strain sensor that can detect scapula movement respecting to the sternum and rib cage in their wearable textile platform. Lin et al. [147] developed a wearable instrumented vest for posture monitoring which received positive feedback from their test participants. Beursgens et al. [148] developed a vest for monitoring the patient posture using a single sensor while playing a serious game intended to support arm-hand rehabilitation after stroke. Next to the reliability of the measures, our emphasis compared to these earlier works shifts more towards aesthetics, wearability, usability, and motivation. Admittedly, obtaining reliable measures is key to the effective use of posture monitoring for rehabilitation. However, aspects like wearability and aesthetics that are key to the acceptance of smart garments have largely been neglected. Another motivation of our research is that higher integration of sensing components into the garment can potentially contribute towards addressing all these concerns. It is noted that wearable systems with bulky sensor units [149] or sensors placed on the arm [14] are not able to track properly the scapular motion. Besides, real-time feedback is also a key function and little effort has been invested in establishing the usability of such systems so far.

With this backdrop, we introduce an interactive garment system, which we call *Zishi*, to support trunk and scapulothoracic motor control training by monitoring compensatory movement and synchronously providing feedback. Our research is a result of six iterations following the approach of research-through-design. We will explain our design and development process, the lessons learned and reflections for each iteration.

Along with the several iterations, we found it's beneficial to shift between the different perspectives. In this chapter, we also present the lessons learned in these different perspectives, using the metaphor of lenses for design. The idea of using the concepts of design lenses to present the design knowledge is inspired by previous work of Jesse Schell [150]and Bekker et al. [151]. Taking different lenses and frequently shifting between them is necessary to take into consideration diverse perspectives and manage diverse requirements. Lenses help focus on a specific part while taking into the overall design goal into account [151].

3.2 Applying the approach of research-through-design

This research builds on the knowledge from therapy, biomedical, sensor technology, engineering, human-computer interaction and industrial design. Given the complexity and multitude of challenges, and in

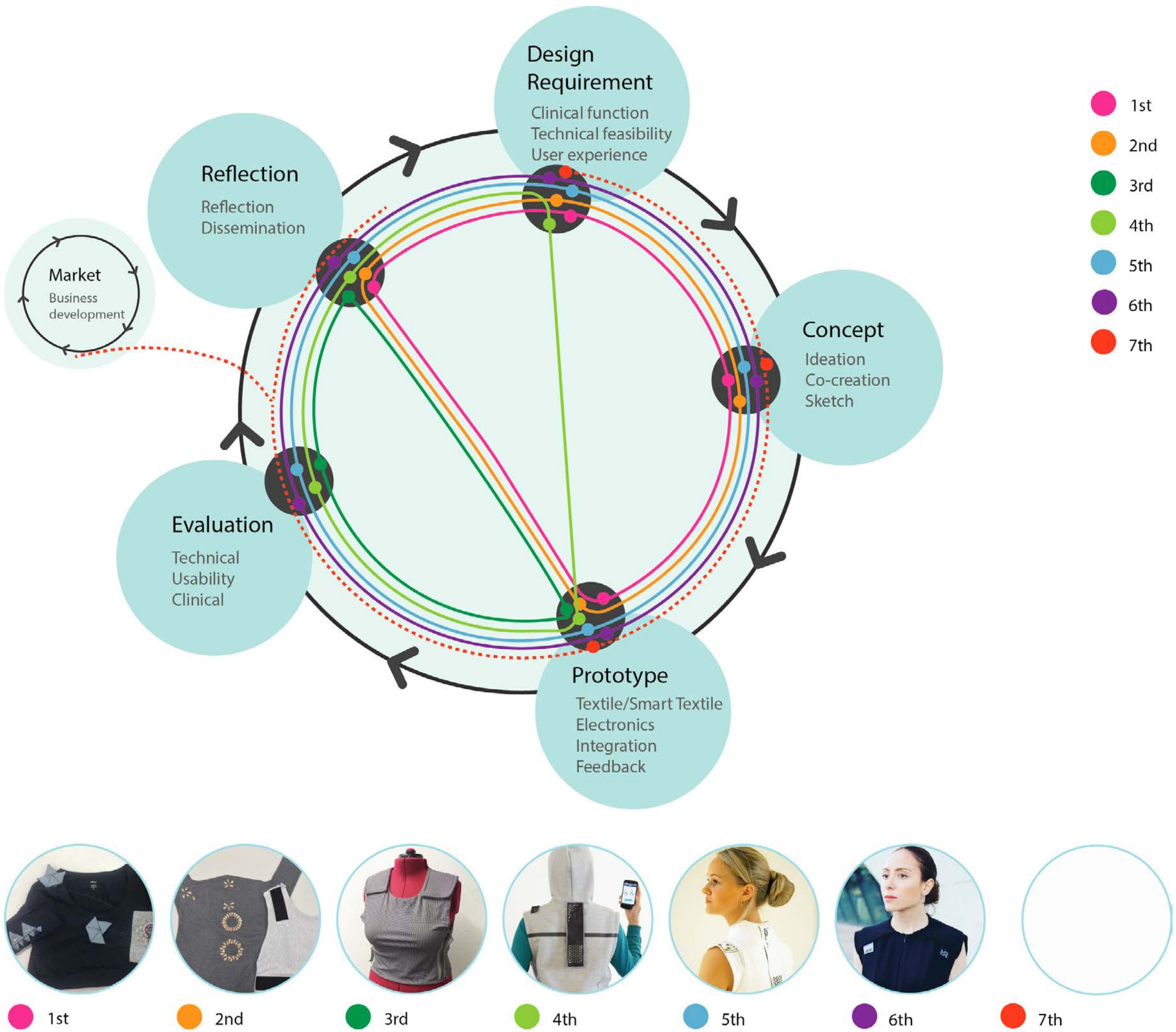


Figure 3.1 Design Process and Iterations Outline.

order to balance the various requirements of function, technology and aesthetic we adopt a research-through-design [71] approach, with the intention of generalizing applicable and communicable knowledge through the development of prototypes.

The approach of research-through-design comprises of methods and processes from design practice, has been used as a common methodology in HCI studies [71]. Following a procedure in a spiral of cycles: identifying the design requirement, ideating concept, prototyping, evaluating potential solutions and reflecting and disseminating the lessons learned. Figure 3.1 illustrates the processes we followed as a sequence of 6 cyclic iterations. At each iteration, the design included making sketches, defining a style concept, materials, form-giving and interfaces design which were presented to the therapists for discussion and feedback. Iterative design and prototyping combined four parallel activities of material testing, electronics, garment making and interaction design [152] (p.108). Each major iteration was followed by an evaluation step during which the various prototypes developed were tested in a laboratory context and, eventually, in a field context. Through the iterative process, we have developed a set of smart sensorized garments and modular solutions that support motion tracking by integrating different sensing technologies and smart textiles, motivation strategy and feedback in multi-modalities. We will describe the general system architecture in section 3.3 and iterations in detail in section 3.4.

3.3 Overview of *Zishi*

In this section, we describe the overview of a smart garment system, which we call *Zishi* (*Zishi* is the pronunciation of a Chinese word ”姿势” which means posture), to support trunk and scapulothoracic posture training by monitoring compensatory movement and synchronously providing feedback. *Zishi* is a result of multiple iterations, and we have been calling the interactive garment system *Zishi* as from the fourth iteration onwards, replacing the acronym SRG (short for Smart Rehabilitation Garment) that we used in the first three iterations. *Zishi* can support trunk and scapulothoracic motor control training by monitoring compensatory movement and synchronously providing feedback directly on the garment and also on a connected tablet/

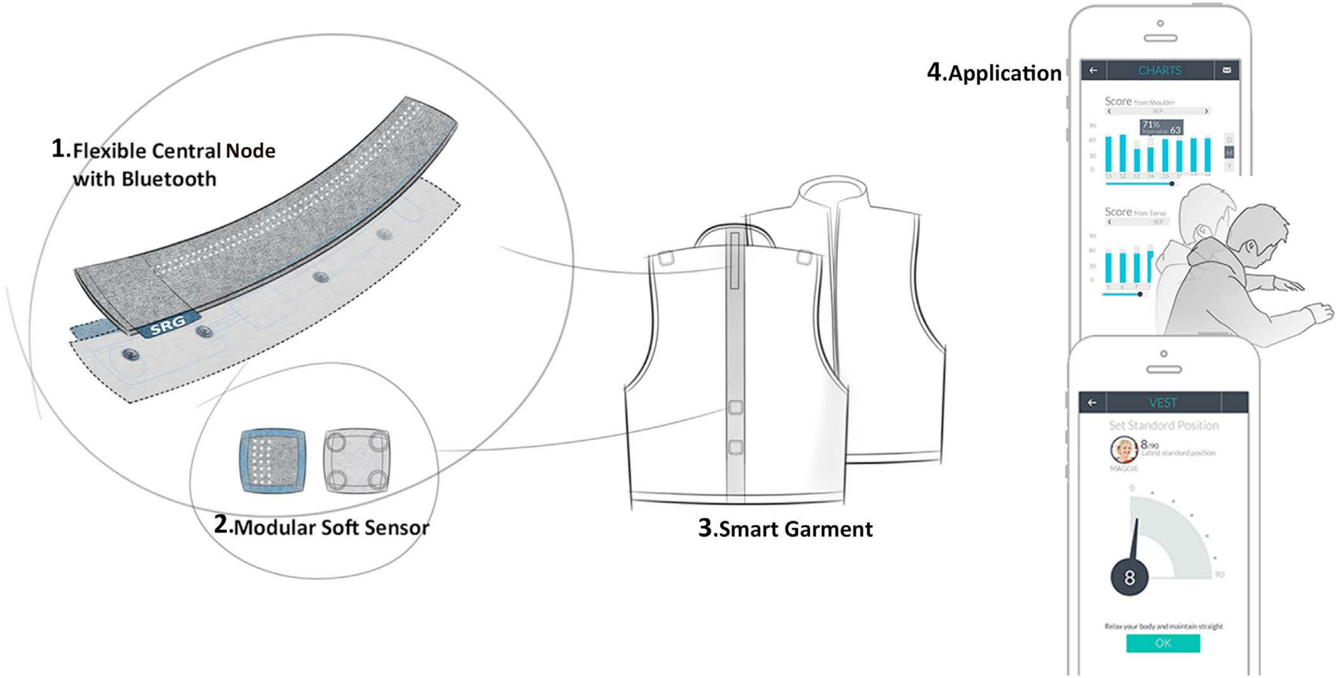


Figure 3.2(a) System Architecture of Zishi

smartphone. While compensatory movement helps patients to achieve their tasks, it can also obstruct the recovery progress and induce orthopaedic problems. In light of this, detecting and preventing compensatory movements warrants particular consideration for technology supported physical therapy treatment. *Zishi* is a garment that resembles in appearance and comfort everyday clothing while it is accurate in tracking posture and easy to use.

3.3.1 Description

Zishi can monitor compensatory movement from different parts of the upper body (shoulder, upper thoracic spine) and can be adjusted to fit the relevant body parts. *Zishi* is a result of the iterative design process, where different components have been integrated into different versions of the garment and evaluated with users. *Zishi* consists of a garment integrated with smart textiles and wearable electronics. It presents real-time feedback as a vibration delivered through the garment, visual and audio instructions through the android-hand held device (smartphone or tablet). Currently, the system architecture is

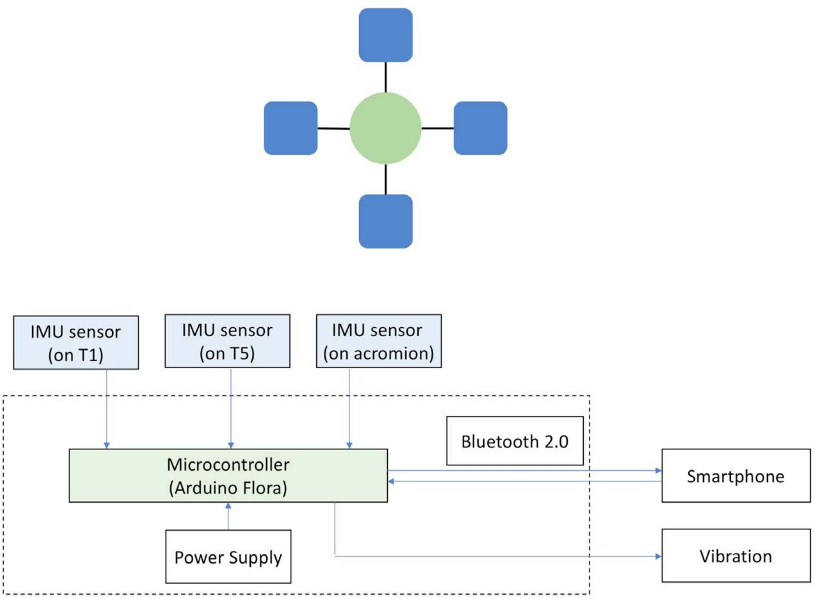


Figure 3.2(b) Star typology and Block diagram of the circuit

shown in Figure 3.2(a), featuring four parts:

(1) A flexible central node equipped with sensors, microcontroller, communication module and flexible circuit;

(2) modular soft sensor units;

(3) a garment integrated with wearable smart textiles and connection points;

(4) a software application that runs on a handheld device.

The modular sensor nodes are physically connected to the central node following a star typology which is easy to implement and extend [153], graphical representation in Figure 3.2(b), to be more specific, the electrical block diagram of the circuit has also been presented.

3.3.2 Calculation Methods

Zishi has been designed to monitor and help prevent two kinds of compensation movements, in the frontal and sagittal plane, which can occur at the shoulder girdle and trunk, to avoid movement at the glenohumeral joint. Compensatory movement of the shoulder girdle is defined as the vertical displacement of the acromion sensor compared to the global coordinate. During rehabilitation exercises with arm movements below 60 °, the scapula should perform a setting, which means that no excessive elevation or depression is allowed (see Figure 3.3a). Scapular elevation means that the scapula slides superiorly on the thorax, as in shrugging of the shoulders (moving the superior border of the scapula and the acromion in an upward direction). The acromion is the most lateral point of the shoulder girdle, and its flat part is a suitable place to put a sensor on to identify whether the shoulder girdle is in an elevated or depressed position following the recommendations of the International Society of Biomechanics (ISB) edcba [19]. At the same time, patients may also develop a slight trunk lateral flexion leading to a lean of the scapula (see Figure 3.3b). Figure 2c illustrates the compensation angle θ, consisting of α and β, which register the vertical deviation of the acromion compared to the neutral position because of the scapula elevation and trunk lateral flexion. The calculation takes as a reference the global coordinate sensor readings in respect to the frontal plane.

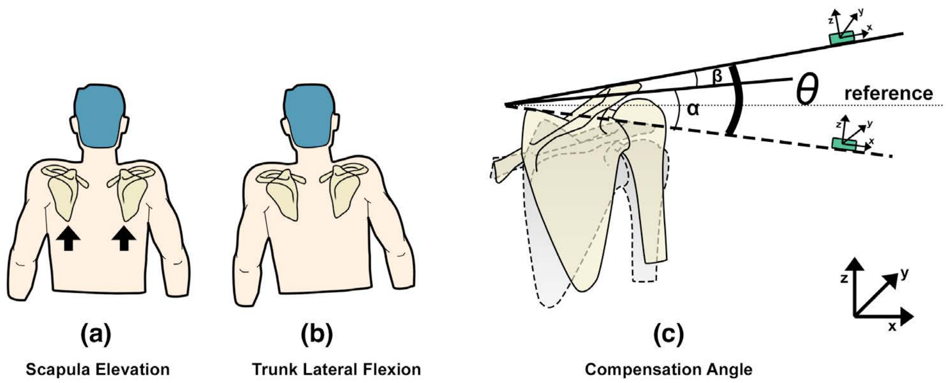


Figure 3.3 Calibration model of the compensatory movement from shoulder girdle.

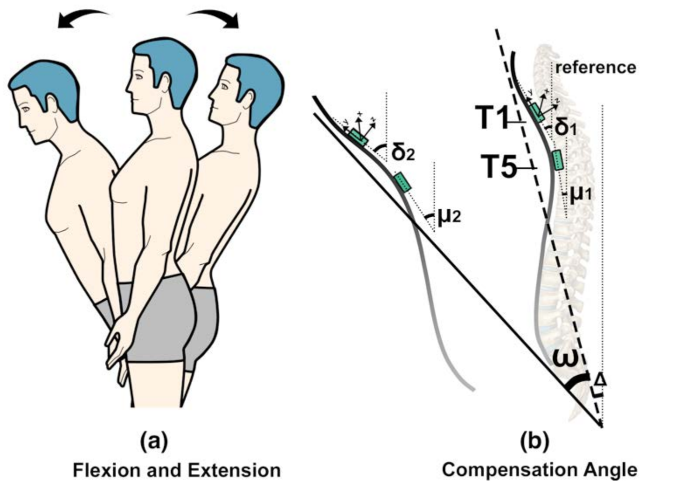


Figure 3.4 Calibration model of flexion and extension movement of torso.

Compensatory movement of the trunk is defined as the additional trunk flexion (anterior displacement) compared to a neutral position, shown in Figure 3.4a. Two FLORA 9-DOF IMU sensors (Adafruit) are used to evaluate the trunk posture regarding flexion/extension accurately. The two sensors are positioned on the spine (C7/T1 and T4/T5) (Figure 3.4b). Sensor locations were based on the evaluation of the initial versions of the Smart Rehabilitation Garment system (reported in [76]). For detecting compensatory trunk movements in the flexion/extension direction, the average of the angles of the sensors with respect to the sagittal plane is calculated, which indicates the upper thoracic angle. When the angles obtained from the IMUs are δ and μ, then the average of δ and μ represents the estimated thoracic neutral angle Δ, and the compensation angle is the thoracic flexion angle ω, estimated as the average variance of δ and μ.

3.3.3 Feedback Strategy

Feedback is important during rehabilitation training, for speeding up learning processes, for augmenting treatment effects and sustaining motivation [67]. Extrinsic feedback can be classified into two kinds: knowledge of results (KR) and knowledge of performance (KP) [67]. Typically a progress in feedback is used. Knowledge of results feedback is more appropriate for beginners, while knowledge of performance feedback is more appropriate for patients who have a higher proficiency level for the required tasks. Typically feedback is provided with fading frequency, i.e. in the beginning real time feedback (even during task performance) is provided, thereafter feedback can be given after task completion or after having performed a set of exercises. They are both important at different stages of rehabilitation and for different purposes. Knowledge of results pertains mainly to feedback regarding the outcome and is typically given after some bursts of training, to keep patients engaged. Knowledge of performance is more important when patients learn a particular skill to complement their own senses in understanding how well they carry out a specific movement. Besides, bandwidth feedback is defined as feedback given only when a movement error exceeds a certain threshold [132] and is beneficial for personalized feedback to individual patients.

Figure 3.5 illustrates an overview of the elements in the user interface. *Zishi* provides both KR feedback and KP feedback. KR feedback expressed as notifications of posture deviations exceed a preset threshold (i.e. bandwidth feedback) to the target user (e.g. red color notification only displays when the compensatory movement over the threshold value). KP feedback expressed as the animation of the visual element mirrored user posture so that user could adjust their posture accordingly (e.g. keep shoulder girdle stable to keep the

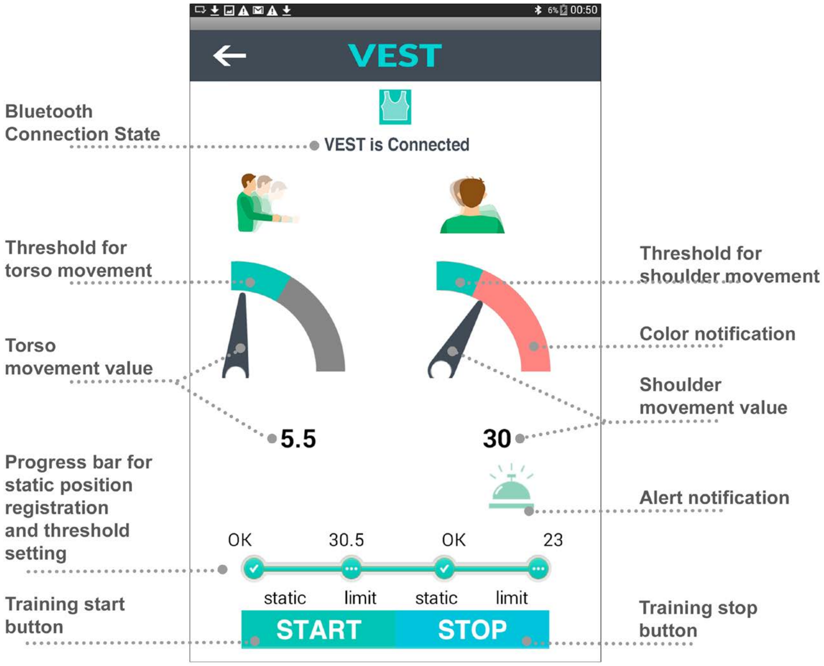


Figure 3.5 Zishi App Interface Design and explanation of the elements

pointer on the gauge rotates within the threshold). *Zishi* provides continuous feedback by means of visual and auditory information through a connected handheld device (smartphone or tablet), and vibration notifications delivered through the garment. The system is able to notify patients when the readings of the sensors exceed their personalized bandwidth.

A therapist can calibrate the device to the patient by identifying a neutral[1] shoulder girdle and trunk postures for this patient and, depending on the goals and progress of training, set a personalized training bandwidth around this position that corresponds to the allowed compensation range. The neutral position (the position in which we calibrate) is the midstance between protraction and retraction, and the midstance between elevation and depression. This procedure works for patients with different pathologies and health conditions. Figure 3.6 illustrates the feedback strategy overview. The horizontal axis indicates the torso data and the vertical axis indicates the shoulder data, the threshold as the dividing lines have

1 We made simply assumption of the calibration procedure: the therapist would register the current neutral/resting position for each trial and the allowed range of movement was assumed to be symmetric around that position. In future work, we shall replace this by capturing with the help of the upper and lower bounds defining the allowed range of movement.

segmented the coordinate plane into four parts, only the movement data within both thresholds would be affirmed as ideal posture and our system would provide feedback in other situations. Contrary to posture monitoring devices that are currently available, supporting consumer technologies, setting personal thresholds is an important step that should ideally be carried out together with the therapist. The application was implemented using the MIT App Inventor (see www.appinventor.mit.edu) that is an online open-source and block-based programming tool block-based programming tool.

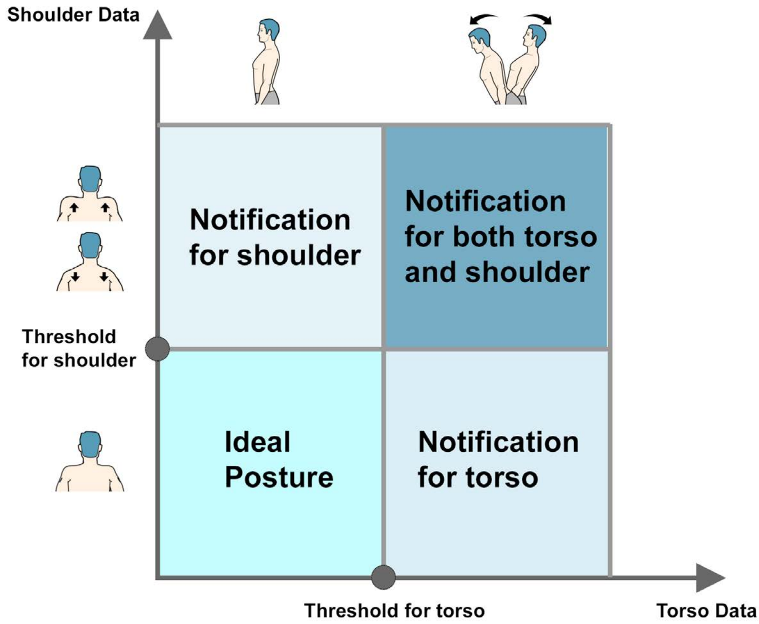


Figure 3.6 Feedback strategy visualized in a coordinate

Figure 3.7 shows the interface during the training execution. The workflow of the application operation is as follows:

In the first stage (a) the user starts the system which pairs the App to the garment automatically. The user's movements are visualized by a rotating pointer and a numerical reading, presenting the movement angle for flexion/extension of the torso (on the left) and the elevation/

depression of shoulder (on the right).

In the subsequent stage (b) the device is calibrated, by setting the neutral position and training bandwidth. Patients may follow instructions to sit in a neutral posture and keep their upper body static to register the "0" point of the scale as the neutral position of torso and shoulder separately. Then the patient is asked to bend forward until the App displays the target threshold that the therapist indicates as the maximum acceptable; this process is repeated for setting shoulder elevation threshold while shrugging the impaired shoulder. The progress bar visualizes the current phase of static position and threshold setting of torso or shoulder.

Figure 3.7c shows the interface during the actual training after the "start" button has been pressed. The green region in the dial shows the intended training bandwidth area. Patients can watch the screen while training and can see whether they compensate excessively and perhaps try to adjust their movement not to exceed the allowed range. The remaining grey part of the dial will turn red if the pointer exceeds the threshold. At the same time, an alarm icon will appear for 2 s with an audio alert and vibration notifications on the corresponding part of the garment. In this way, users can be made aware of their compensatory

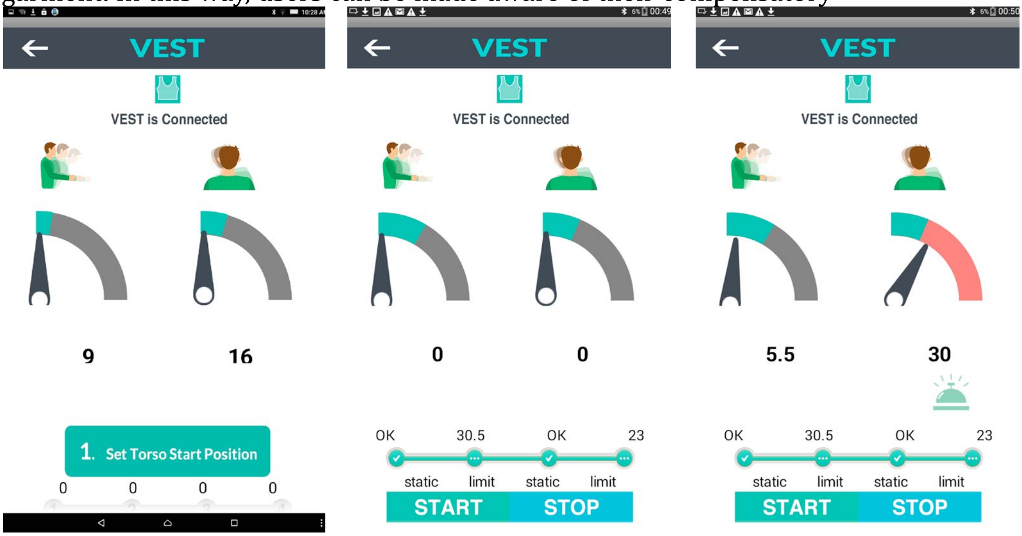


Figure 3.7 Zishi App interface design in different stages: (a) Automatically connected. (b) Set personalized value of start position and threshold. (c) Visual feedback when the shoulder value is over range.

movements and learn to control them. The customized threshold setting serves as a reference target for each motion cycle. Providing real-time feedback, we aim to support correct movement execution and enhance motor learning, and thereby training effectiveness.

The sampling frequency of the sensor system is 50 Hz, while the frequency of the visual display (pointer rotation) was set at 30 Hz because to ensure a smooth visual display on the smartphone. During the experiment, subjects performed the tasks in a controlled manner (i.e., no explosive movements), similar to their daily training. In this way, the system is capable of monitoring the posture in real-time and providing subsequent feedback with inconspicuous delay.

3.4 Design Iterations of *Zishi*

This section provides an overview of each design iteration by identifying its main aim, describing the improvements of *Zishi* in each iteration, presenting the evaluation steps and a short reflection on lessons learnt on the way.

3.4.1 Iteration 1-Embedding accelerometers in a T-shirt

Figure 3.8 All the materials and tools used in the first iteration.

Figure 3.9 Prototype in the first iteration. Two Lilypad accelerometers and a Lilypad Arduino board were sewn on non-woven fabric separately and could be attached on the T-shirt with snaps. Sewable LED lights provide on-body visual feedback.

Aim: as the start point of exploring how wearable technology could support rehabilitation and following research-through-design approach, we set out to create a posture tracking T-Shirt in order to identify the main technical and design challenges and to seek design opportunities.

Key Actions: We consulted and discussed with experts in upper extremity rehabilitation, and decided to narrow down the purpose of SRG to help rehabilitating stroke survivors avoid compensatory movements during arm-hand function training. To ensure correct execution of arm-hand training exercises, we decided to track the trunk flexion movement. First, we experimented with different sensors for posture monitoring, e.g. mounted a flex band sensor on the spine from the C7 vertebrae to monitor trunk flexion while it was not long enough to cover the target area. Eventually, we built up a simple system where two sewable LilyPad accelerometers (on the chest and acromial base) and a LilyPad Arduino were attached to an off the shelf commodity long-sleeved T-shirt. Data was communicated through a serial port with a computer to display real-time measurements corresponding to the movement. Figure 3.8 shows materials and tools used in the first iteration and Figure 3.9 shows the finished prototype.

Reflection: this iteration provided the opportunity to familiarize with the problem domain and the technology, resulting in an initial proof of concept demonstrating the feasibility of monitoring of trunk flexion and extension using a T-Shirt. However, it became clear that the measurements were not sufficiently accurate and stable and improvements could be gained by a more careful and principled placement of sensors to the body.

3.4.2 Iteration2-Garment embedded smart textile pattern and Bluetooth communication

Aim: to implement a comprehensive garment that supports minimal functionality to be viable as a therapy aid. Further, we aimed to increase the reliability, accuracy, comfort and aesthetics of the garment.

Key Actions: we conducted explorations from the following four aspects to build a complete smart garment system (published in)[64, 75].

Figure 3.10 Garment and textile pattern in Iteration 2

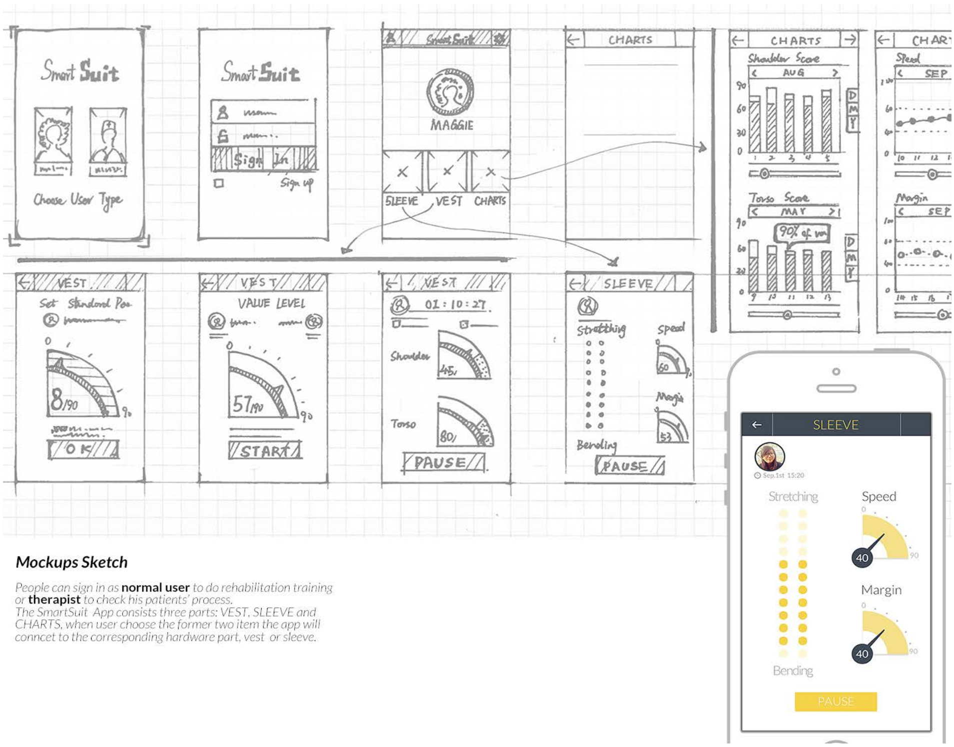


Figure 3.11 Mock-up sketches for the interface design.

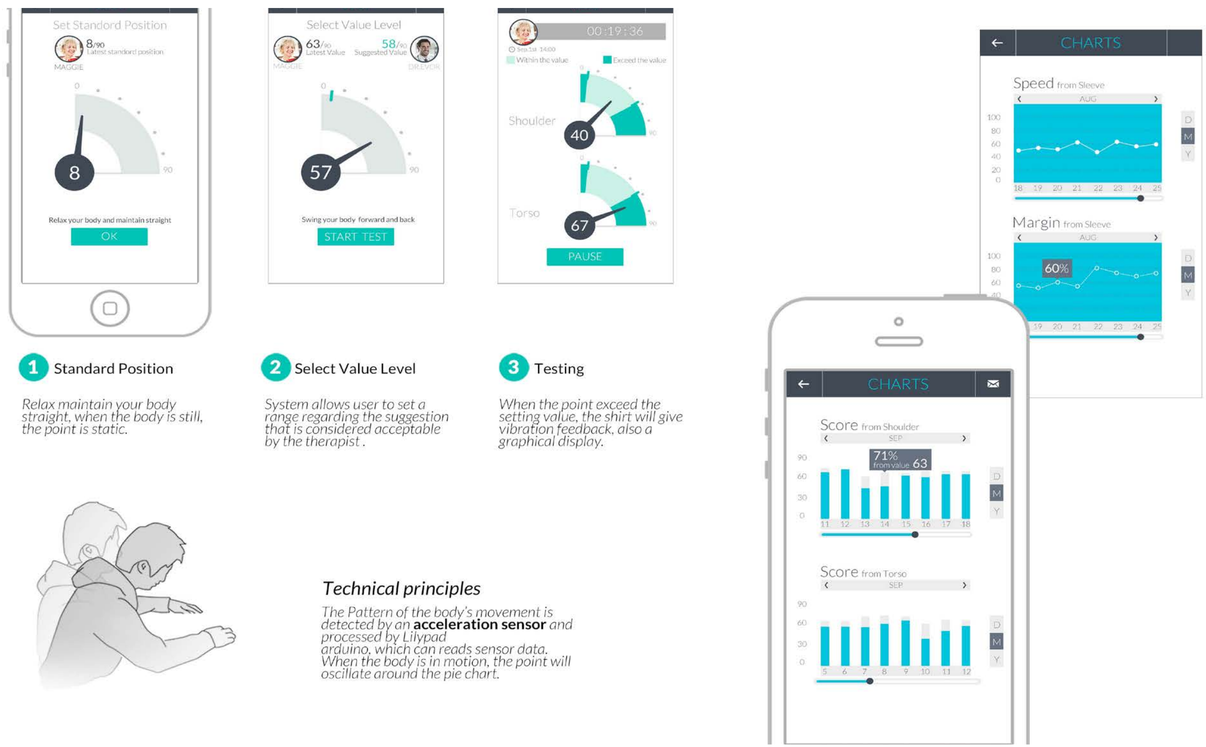


Figure 3.12 Visual design of the interface: in the left part of this figure in green a rotation pointer indicates body posture to the right an overview of posture data over time is shown as a graph.

a) Elaboration of appropriate sensor placement. We placed two sensors on vertebrae C7/T1and T4/T5 on the spine instead of one sensor on the chest, to capture thoracic posture and torso compensation movements.

b) We tested different conductive yarns and conductive textiles (the golden colour textile thread in Figure 3.10) with various properties, proposed smart textile pattern (conductive fabric from Shieldex®) as a substrate for embedding electronics.

c) Garment design as the 'platform', Figure 3.10 demonstrates the prototype was an adjustable garment with two pieces with detachable front and back parts. Combined with the elastic fabric, this concept provides a solution for fitting people of different sizes, without influencing comfort by tightness; this is a key factor for correct position of the sensors during spinal movements and may also be very important for supporting long-term use.

d) Real-time feedback of the monitoring results, an Android-based application was developed to control the garment; the number of trunk flexion angle was transmitted via Bluetooth and displayed on a Smartphone. Figure 3.11 illustrates the mock-up sketch and Figure 3.12 shows the visual design of the interface. The LilyPad Vibe Board was embedded closed to the accelerometer provide vibration feedback.

Reflection: this study was an entry point into the domain of crafting e-textile and electronics, and developing skills for the wearable prototype implementation. We explored how using smart textiles in wearable projects can contribute to the implementation of reliable and comfortable designs, which can reliably relay electrical signals and digital information to monitoring systems. Also, we started paying closer attention to the design of the feedback to end-users

3.4.3 Iteration 3-Interactive garment with IMU sensor and personalized feedback

Aim: to design a posture-sensing garment that supports two different training scenarios: first, sustaining an upright position in daily life for avoiding spinal pain and second, notifying patients of any compensatory trunk movements during arm-hand training (for neurological patients).

Key Actions: In this iteration, the accelerometers were replaced by inertial measurement units (IMU) integrating an accelerometer, a gyroscope and a magnetometer thus improving the accuracy and stability of measurements. In this iteration, we experimented with a modular design consisting of multiple sets of garments and one set of wearable sensors. A mobile Android application was developed. A circuit connecting the wearable sensors and other components was realized by embroidering conductive thread. The resistance of the conductive garment was calculated based on the sample of the conductive threads, the conductive yarn used in the garment with a resistivity under 100 Ω/m, and by adjusting the conductive paths to balance between the aesthetics of the embroidered pattern on the garment and the resulting resistance value. We compared the accuracy of the measurements (published in [76]) against a commercial optical tracker system (PST-55/110 series) that uses infrared lighting to detect optical markers from ps-tech (see www.ps-tech.com), one L shaped hard piece with two optical markers was attached to each sensor (Figure 3.13 was the screenshot during the experiment from the software of the optical tracker).

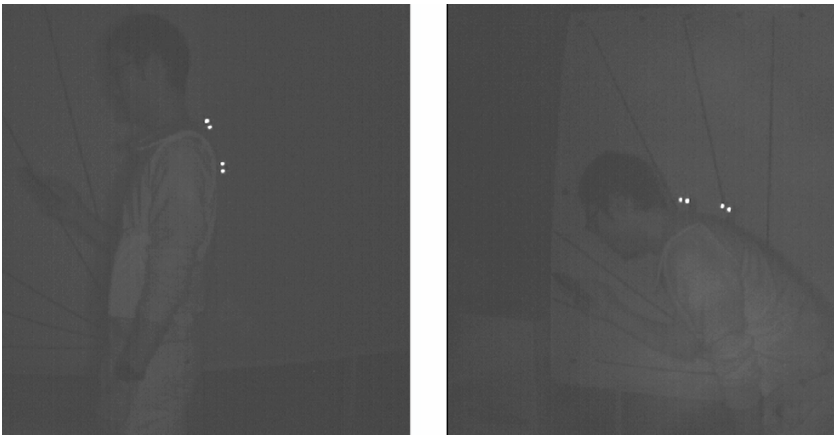


Figure 3.13 A Participant was performing the movement of trunk flexion with infrared marker located at the sensor placements

Reflection: Based on the data analysis from the seven subjects in the experiment, the accuracy achieved was comparable to current state of the art in wearable sensors for rehabilitation [21]. Our system could provide reliable feedback and performance on measuring the thoracic angle. While the deployment in clinical or home context need further exploration and usability evaluation.

3.4.4 Iteration 4- *Zishi*, Reconfigurable smart garment system

Aim: the garment developed in this iteration targeted at rehabilitation training for shoulder pain patients and stroke patients with limited arm-hand function. We set out to examine the system's applicability and the acceptance by patients and therapists.

Key Actions: we focused on an adjustable design of the shoulder part and improving the reliability of the readings compared to previous versions. For this, we embedded conductive yarn in a Z-stitch pattern in the elastic fabric. The system consists of four parts as described in section 3.3.1. Figure 3.14 illustrates the *Zishi* prototype in this iteration.

The flexible central node consists of the following components:

1) two IMU sensors with 9 degrees of freedom (Adafruit, USA), containing an accelerometer, a gyroscope and magnetometers;

2) a multiplexer board to support multiple sensors in the system;

3) a Bluetooth module for wireless communication between the microcontroller and smart device;

4) FLORA, an Arduino-compatible microcontroller to which all other components are connected to;

5) 3V lithium battery. A laser-cut conductive textile pattern was applied as the flexible traces to connect the electronic components (shown in Figure 3.15a).

In order to make it easier to wear, we tried a zipped garment made of soft materials in this iteration. With the intention of guarantee a precise shoulder sensor placement over time in the pre-defined position, the sensor is flat (height 0.8 mm, diameter is 16 mm) and sewn by coated conductive yarn on a soft elastic strap (Figure 3.15b) with a Velcro-fastened at its end. One side of the strip was fixed on the garment while the other side was flexible for adjustment (Figure 3.15c). Thanks to the adjustable design, the sensor could be positioned at the flat part of the acromion of different patients. The movement of the acromion during the exercises is very limited, i.e., the exercises require keeping the scapulothoracic joint still while the arm is elevated within the limited range of motion that is possible without scapulothoracic movement. Thus precise sensor positioning was ensured by having a garment at different sizes and fine-adjusting with the Velcro fix. Aiming for an unobtrusive and comfortable garment, coated conductive yarns were sewn on the garment, to serve as a

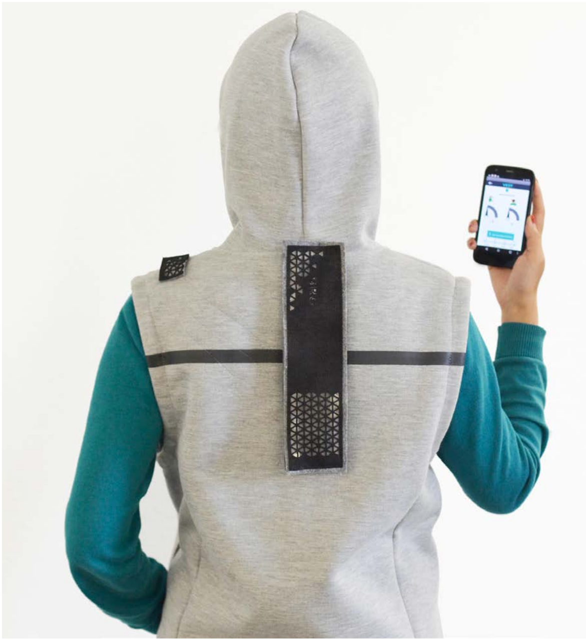


Figure 3.14 A user demonstrating the prototype of the forth iteration of Zishi with detachable black part on the back as the central node, modular soft sensor located on the acromion, conductive yarns were embedded in the garment and app presenting the visual feedback on smartphone.

(a) (b) (c)

Figure 3.15 Garment in Iteration 4: (a) Conductive textile-based traces. (b) Sensor embedded in a Velcro strap by coated conductive yarn; (c) Velcro adjustments;

fabric-friendly embedded circuit for connecting the sewable electronic components described above. In this way, the garment resembles daily clothing with the aim to improve user acceptance, see Figure 3.14. This prototype was evaluated for use in training of shoulder patients (Figure 3.16) in a study involving eight patients with musculoskeletal shoulder pain (reported in [154] and describe extensively in chapter 4 of this thesis). Besides, another application named ZUOZI has been designed focused on shoulder posture which supports two modes of operation, a "shoulder trainer" mode and a "continuous shoulder tracker" mode, the study will be presented in Chapter 5.

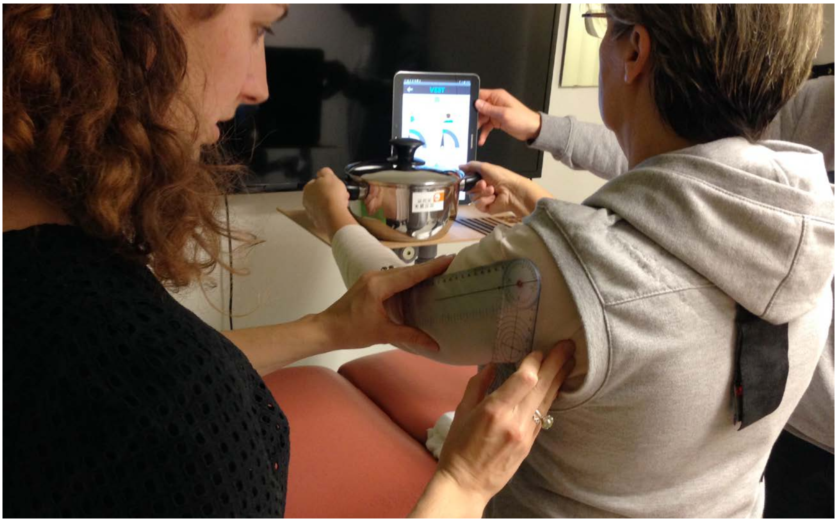


Figure 3.16 A participant was performing the training task with Zishi during the experiement, she would perform a task of placing a cooking pot, a therapist was calibrating participant's arm movement as a standard setting standing on her left side.

Reflection: with this iteration, we aim to demonstrate the effectiveness of the garment in providing feedback to patients during training. Different feedback modalities can be beneficial at different stages or to serve different training tasks. For instance, during the analytical tasks like an abduction to 40 degrees, the subject could easily follow the visual guidance and adjust their posture to stay in the personalized movement range. During the functional tasks like lifting up a bottle, system feedback was restricted to the periphery of the subject's attention, so audio notifications and vibrations were easier to follow than detailed visual feedback. However, feedback from users, experts, and other designers emphasized that the aesthetics of the garment still needed to be improved.

3.4.5 Iteration 5 – Fashionable *Zishi* with smart textile pattern and magnets-based connections

Aim: this iteration aimed to demonstrate the effective integration of wearable electronics into garments with a fashionable appearance.

Figure 3.17 Fifth Iteration, One model demonstrating Zishi, the garment looks like a normal and fashionable vest.

Key Actions: we carried out explorations on improving the aesthetics and integration level by:

1) trying out various fabric samples considering the factors of colour, hand feel and style in order to make the final choice of fabric that was integrated in the final prototype shown in Figure 3.17 and Figure 3.18;

2) designing the structure of the garment, featuring a turtleneck design fit the sensors on vertebrae T1 and T5, allowing the concave surface design of the garment to act as a natural place for attaching the flexible sensor pad (published in [123]);

3) a conductive fabric was processed into a specific pattern by laser cutting and it was then transferred through heat transfer paper (see Figure 3.19a); a tiny magnet (3mm in diam.) has been placed under each of the small golden square fabric as the connection point (see Figure 3.19b).

Figure 3.18 User familiarizes with system feedback when the elevation movement exceeds the set threshold

(a) (b) (c)

Figure 3.19 Conductive fabric pattern with a magnet-based connection. (a) Conductive fabric pattern was integrated into the garment, and the white garment is washable while the central sensor package is taken off; (b) Sensor package was attaching on the garment, the connection was based on tiny magnets placed under the small golden square conductive fabrics and the white magnet zippers on both sides; (c) circuit pattern in the sensor package.

Reflection: Compared to previous version the design of Zishi emphasized on aspects like being physically intimate, allowing high mobility, and being visually expressive. This garment could easily conductive threads provide connections with the modular wearable sensing unit as decoration without compromising the aesthetics qualities of the garment. The pattern design was created iteratively aiming to balance the resistance of the sewn circuit (conductive fabric) and its appearance; we experimented with different patterns before settling with the final embroidered pattern shown in Figure 3.19c; different patterns we tried were evaluated for their functional as well as their stylish properties.

3.4.6 Iteration 6 – *Zishi* with Sound feedback

Figure 3.20 The sixth iteration of *Zishi*, electronics are concealed in the garment with central package on the back and sensors are located on the acromion and sternoclavicular joint.

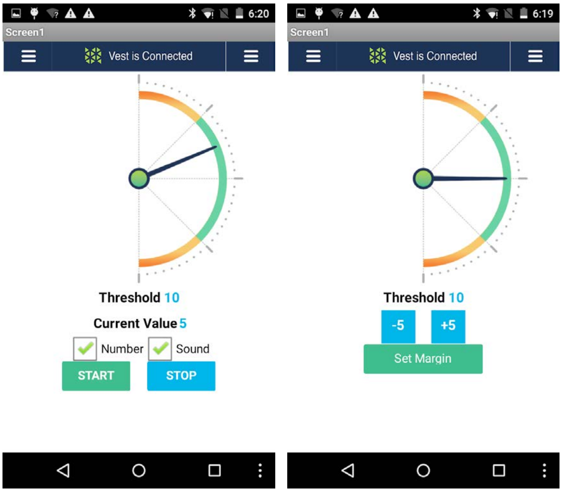


Figure 3.21 Interface Iteration. (a) checkbox for function of number display and earcon feedback. (b) threshold setting with add/subtract buttons.

Aim: this iteration examined the combined "protraction/retraction" and "elevation/depression" monitoring, in order to support shoulder motor control training.

Actions: the shoulder complex and the cervical spine are closely linked, the sensor locations were reconfigured with one sensor located on the acromion and a reference sensor located on the flat part on the sternoclavicular joint. We implemented a new algorithm that is able to distinguish shoulder protraction from upper body rotation. After the pattern design of the garment construction, sewing and tailoring, the garment is as presented in Figure 3.20. The application was improved to provide sound feedback that reflects movement qualities, with the earcon frequency [155] increasing as the compensation movement approaches the threshold. A checkbox is also provided to enable or disable the sound and numeric display (see Figure 3.21a). Another modification is that users can set the threshold using the add/subtract buttons instead of logging at a specific point in previous iterations (see Figure 3.21b).

Reflection: In this iteration, we gained experience in the integration of conductive materials in the garment and proposed some ways to enhance system interactivity with real-time feedback.

3.4.7 Self-reflection of the iterations progresses

Figure 3.22 illustrated how we mapped the iterations onto the layers of user requirements as function, usability and engagement, adapted from Aarron Walter's emotional design pyramid showing the hierarchy of user needs in the book "Designing for Emotion" [156].

Looking back at this iterative design process our emphasis has shifted between different design aspects. We can distinguish three different layers that have been addressed in parallel addressing respectively different classes of design concerns. Different iterations did not take on individual issues in isolation but rather, addressed them all in combination while placing a different emphasis each time.

The first layer (see Figure 3.22) emphasizes on functionality, accuracy and interactivity as basic requirements for building the system, accurate monitoring and real-time feedback are the foundational features, the third iteration with accuracy experiment was our milestone for this layer. The second layer addresses the aspects of ease of use, comfort

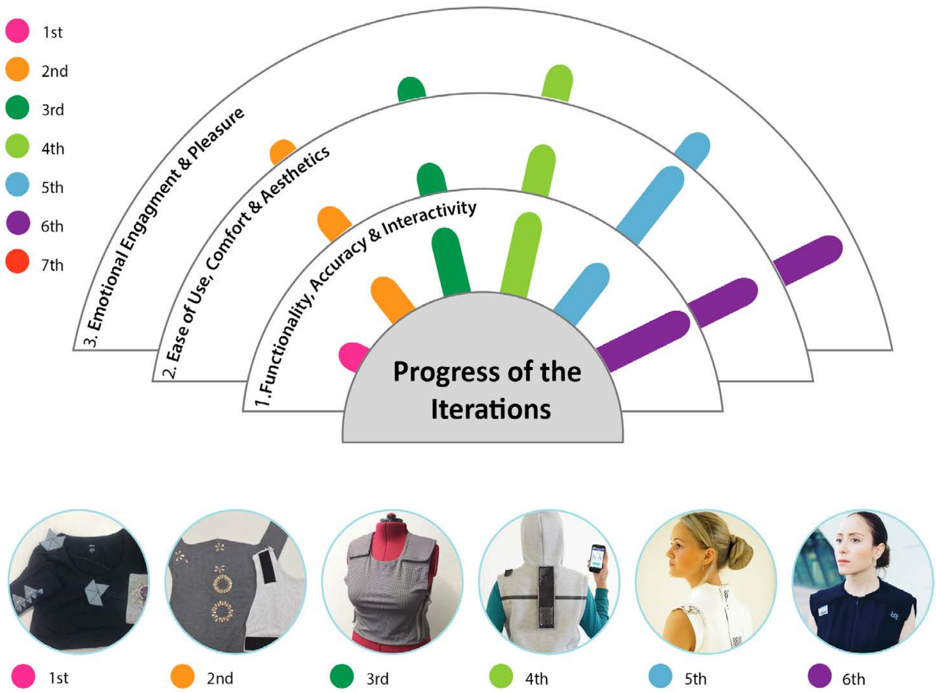


Figure 3.22 Progresses of the iterations

and aesthetics which are our key contributions. We constantly gained experience in each iteration and the fifth iteration with a fashionable and comfort garment was a milestone in this respect. The third level concerns emotional engagement, aiming for a delightful experience as a motivating system focus on personalization, pleasure and even games. The fourth and sixth iterations focused on these aspects more.

Since we didn’t conduct formal evaluation study for every iteration in the same setting, Figure 3.22 is not a concrete conclusion, however, it’s a self-reflection how the interactive garment system has been improved through the iterations we conducted step by step, it’s also a self-assessment about our explorations.

3.5 Design Lenses for Interactive Posture Monitoring Garments for Rehabilitation

3.5.1 Design Lenses

The iterative design of Zishi has taught us several lessons regarding how to interactive garments for rehabilitation pertaining to different aspects in this domain such as how to track movement, the feedback design, performing evaluations, etc. In this section we attempt to summarize them in a way that might allow these lessons to be used and extended in different design projects.

There are significant challenges and practical barriers to face when designing interactive wearable garments for rehabilitation, and there have been several attempts to compile related guidance by researchers from different research traditions such as biomedical science, engineering, rehabilitation, computer science and design. For example, Seymour [62] discussed factors for fashionable wearables including body ergonomics, perception, functionality, technology, materials, energy and environmental impact; Hadjidj et al. [32] listed challenges in wireless sensor networks for rehabilitation combining application requirements and system characteristics of wearability, comfort, durability, accuracy, safety and interactivity; Pantelopoulos et al. [69] summarized essential evaluation features for wearable sensor-based systems for health monitoring; Nugroho [157] introduced a set of design attributes for designing wearable technology including size, washability, durability, fabrication, connectivity, sensation, usability, functionality, device position, power source, heat and weight; Andreoni et al. [158] discussed considerations for sensorized garments on technological features (e.g. sensor design and materials) and design requirements (anthropometry and garment features), they also proposed a decision tree visualizing the interdependent points; Tomico et al. [159] made broad recommendations by presenting design cases and recently, Postolache et al. [160]discussed the technical and technological issues related smart clothes for rehabilitation, with more focus on the implementation smart clothing. Though these studies provide a valuable resource, they do not yet provide high-level practical strategies towards designing and developing interactive garment system for rehabilitation.

Design lenses are a way of presenting design considerations and patterns that address high-level perspectives with a set of focusing parameters [151, 161]. Design lenses originate in the area of game design [150] and have been adopted also in the area of user experience design. Our presentation follows the approach by Bekker et al. [151] who proposed a toolkit containing four lenses of play and presented how these can be applied in designing playful interactions. The idea of 'lenses' as a metaphor stands for the need to shift between different perspectives and focus on specific questions without losing sight of the broad direction. Each lens captures a coherent and distinct perspective, they are relatively separated from each other, but overall lenses have to be addressed in a combined matter in the design.

We adopt lenses as a way to describe the design of Zishi as: a) they help describe design considerations in *Zishi* from different perspectives, rather than tracking every decision in a historical order (which would be tedious and dilute attention from the core design decisions); b) they help exemplify how the lenses can be applied and what is their added value.

An inventory of design considerations for wearables in rehabilitation was built on the basis of the above mentioned studies. We reread the 46 articles included in the systematic literature survey and the 6 publications describing our iterations on *Zishi*. In this process we tried to identify the design considerations, aims and challenges. 102 insights (35 from *Zishi*) have been extracted and written down on separate notes. Subsequently, these have been clustered inductively insights (using the approach of affinity diagrams [162]) into six groups which cluster related design aspects and which are presented below as design lenses: Function, Reliability, Interactivity, Wearability, Aesthetics and Hard & Soft connection. Figure 3.23 illustrated an overview of the lenses including their more detailed elements and the appropriate stage to consider in a general system architecture of an interactive smart garment. The dashed lines show the physical relation of the elements in the system architecture as part of sensing and feedback modules that could be attached/embedded/integrated into the smart garment.

In the following sections, a we will illustrate the key points contribute to each lens and discuss how each lens can contribute to the specific design decision by taking the abovementioned design iterations of *Zishi* as examples.

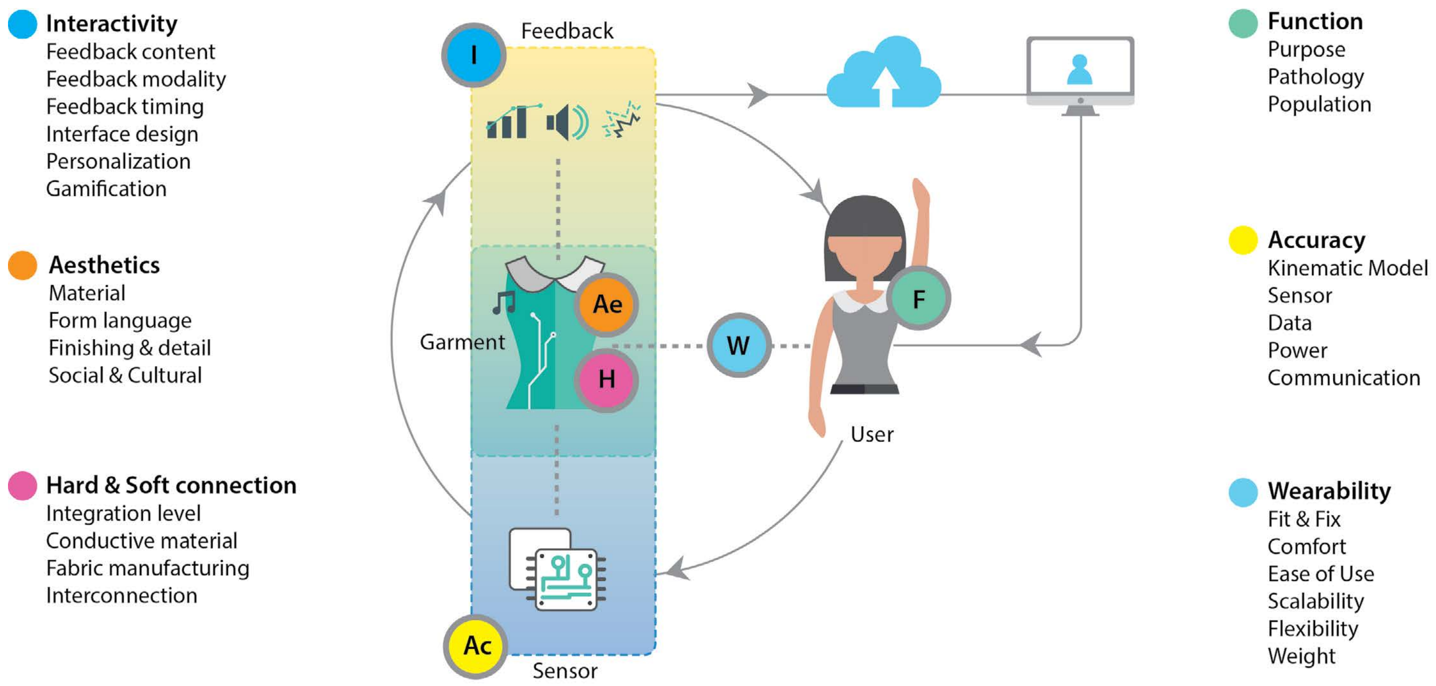


Figure 3.23 Overview of the design lenses. The middle part presents a general architecture of interactive garment system, sensors could capture user's data and feedback present useful information to users in different modalities. The garment could integrate part of the sensors and feedback modalities as a wearable system. The six design lenses have been mapped at the most relative stage.

3.5.2 Lens of Function

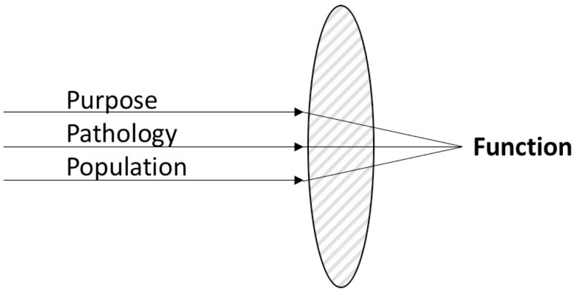


Figure 3.24 Lens of Function

The lens of function considers the purpose of the device, the pathology it addresses and the target user group (see Figure 3.24). This lens represents priorities originating from a clinical context. For example, Timmermans et al. [11]proposed criteria related to therapy for sensor rehabilitation technology, Hochstenbach-Waelen and Seelen identified therapy-related criteria technology should meet to assist rehabilitation [163]. Both these studies recommended that technology should be patient-tailored and goal-tailored.

To guide design is essential to have a clear definition of the target population and the specific rehabilitation aim as, for example: improving the active joint range of motion, improving movement performance, improving movement coordination, improving posture, improving muscle strength, overcoming learned non-use and improving performance of ADL (activities of daily living) skills, improve social confidence, etc.[34]. It is worthy to consider how the system could contribute to the existing therapy [29] or even contribute to creating new therapy [19]. Wearable systems for movement and posture monitoring can track various parameters regarding the body segments and joint kinematics, such as: range of motion (movement distance around joint or body part), amount of use (activity amount of body segment) or body segment posture (specific posture or body segment to target spatial location).

Applying the lens of function

The lens function requires multi-disciplinary input and participatory approaches. During the development of *Zishi*, we collaborate closely with researchers from the Biomedical research institute in Hasselt University, specifically on the efforts related to applying the lens of function. This lens was beneficial for our project in two ways:

1) Applying the lens of function helped us understand the user needs and to set a research direction. When the project started, we firstly had an indistinct direction of supporting arm-hand rehabilitation by wearable systems. We needed to make sure our chosen direction was meaningful from a clinical perspective, so we consulted relevant literature and we could benefit from "real-life" knowledge by meetings with therapists, regarding how rehabilitation therapists address the challenge of self-awareness of compensation movement. Consequently, the design goal was shaped with the clinical experts to improve the upper body posture by reducing excess trunk flexion. During this process, we also were able to define more precisely the target user group, which at the first stages of the project was elderly stroke survivors. In later iterations, we could adjust this focus to exploit the opportunities offered by Zishi for different target user groups (shoulder patients and office workers).

2) Another aspect was the generation of new design concepts. Applying the lens of function in the stage of evaluation and reflection of the accomplished prototypes help us extract new design challenges (e.g. to monitor protraction and retraction movement with shoulder pain patients during the 4th iteration). Apart from regular meetings to steer the direction of the project, a creative workshop was held in which clinical researchers and design students participated to investigate different ways of providing posture feedback.

3.5.3 Lens of Accuracy

This lens draws attention to monitoring reliability (see Figure 3.25). To be applied for rehabilitation the garment needs to provide sufficiently reliable data. This lens concerns the kinematic model, sensor type, sensor locations, calibrating algorithms, data processing and storage, wireless communication and power supply.

Understanding of the kinematics of the body segments is essential to describe the angles and motions of the body segment. There is already substantial guidance for designers as, for example, the guidelines of International Society of Biomechanics (ISB) [164]. The orientation

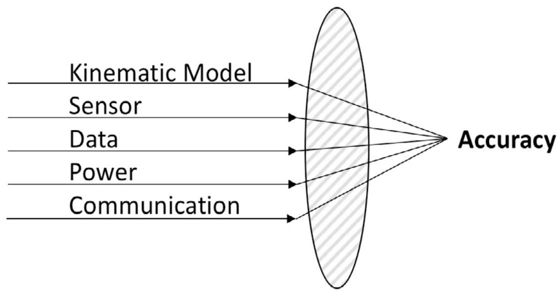


Figure 3.25 Lens of Accuracy

of the anatomical system of reference could be computed according to the system of reference of the sensor unit following the approach described in [165].

The main options considered during the development of *Zishi* regarding the sensor technology were: 1) Accelerometer/IMU; 2) Flexible angular sensor; 3) E-textile; 4) Others. Systems based on accelerometer or IMU measurements normally consist of several sensor nodes and can measure kinematic parameters such as orientation, position, velocity, as well as complex body posture and joint range of motion. A flexible sensor is suitable for sharp joint motion tracking. An e-textile sensor refers to the textile-based sensors (textile capacitance sensor, piezoresistive sensor, etc. [38]) with high requirement of sensor placements. When determining the sensor location, it is essential to consider the kinematic model and sensors properties.

A decision that has to be made for data is how much pre-processing, e.g., simple motion estimation and noise filtering, should be done on the microcontrollers embedded in the garment, versus those done on the connected Smartphone device. This depends on the computing power of the embedded processor and the requirements for communication with the connected device, as pre-processing helps reduce the amount of data that needs to be transmitted [59].

Power and Communication [166] are also fundamental considerations for the system architecture. Currently, rechargeable Lipo batteries are very widely used. However, due to the challenge of building a small and flexible device, other approaches can be considered that will reduce the need to add hard and relatively sizeable components: energy harvesting and distributed power management (e.g. solar photovoltaic technology [167] , integration of piezoelectric materials [166], etc.).

Integrating such possibilities was outside the scope of this research but could be useful to ensure longer autonomy and sustainability for the device.

It is beneficial to consider both short-range and long-range communication for smart garments [152]. Short-range communication could be implemented by conductive yarns or other conductive material processed by textile machinery in an aesthetic way [152] (p.21). Another way of short-range communication is wireless communication. Typically, smart garment systems are paired with hand-held device and demand real-time communication (e.g. Bluetooth, Wi-Fi and Zigbee) for data transmission. The system with multiple electronic modules are mostly wired connections (e.g. conductive material), should be designed with attention on another lens: hard & soft connection. Smartphones can also support telecare scenarios by connecting to secure cloud services.

Applying the lens of Accuracy

The key design decisions we made for high reliability by applying this lens were listed as following:

1) Sensor and calculating algorithms. We have experimented with accelerometers, flexible sensors, piezoresistive fabric and IMU sensors. Accelerometers and IMU sensors were eventually adopted because of their small size, high accuracy and the ease with which they could be integrated embedded in with fabrics.

Regarding to the orientation angles, our first approach which is illustrated in Figure 3.26, assumed a axis in the target local coordinate frame is parallel with the world coordinate frames. When the sensor is completely stationary, the measured vector ga of acceleration due to gravity points vertically upwards and the intensity equals to g ($9.81 m/s^2$) [168]. In this way, the formulate for calculating the angle around y axis based on the accelerometer readings (ax, ay, az), as follows: $\varphi = \pi/2 - \arccos|az/ga|$.

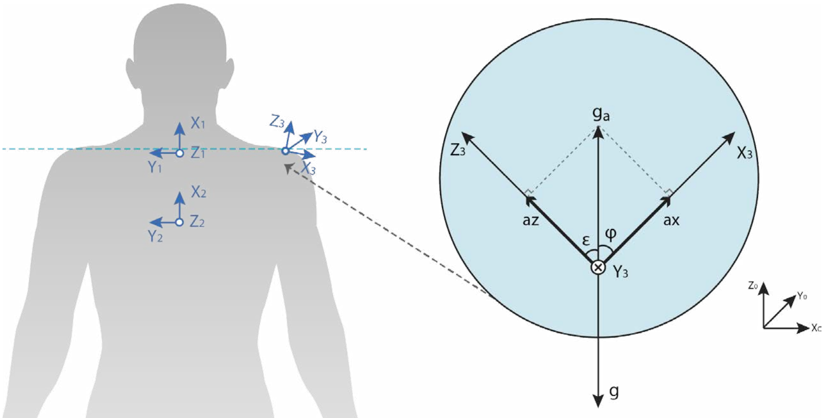


Figure 3.26 first orientation calculation method.

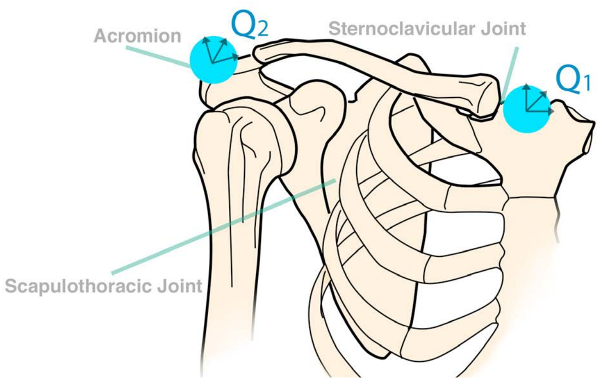


Figure 3.27 second orientation calculation method for relative movement body segment monitoring, blue dots show the sensor locations.

In the sixth iteration was adapted this calculation to calculate the relative motion of different part of human body instead of estimating the relative motion of human body segment with respect to the world coordinate system. Furthermore, the initial condition of the sensors placed on acromion joint and sternoclavicular joint is also considered (see Figure 3.27). Since these two local coordinate systems are not necessarily parallel, their initial relative relation varies when being applied to different bodies. The module embedded in the latest iteration was Adafruit-BNO055 IMU module and its built-in fusion algorithms provide absolute orientation and quaternion data, which is essential for the subsequent protraction calculation algorithms.

If we denote the quaternion of the sensor placed at sternoclavicular joint as Q_1, the quaternion of the sensor placed at acromion joint as Q_2 and the quaternion Q_0 presents information about the relation of the attitudes of each sensor under initial condition. While the initial relative relation should also be estimated based on a calibration phase (i.e. keeping still in a neutral position and reading the quaternions output of 2 sensors representing their rotation regarding their respective world coordinate systems).

Let Q_1 and Q_2 denote two rotation matrices R_1, R_2 and R_1, R_2 are orthogonal matrices. Denote g_0 as the representation of gravity in the world coordinate system, g_1 as the measurement of gravity in the local coordinate system corresponding to the sternoclavicular joint and g_2 as the measurement of gravity in the local coordinate system corresponding to acromion joint.

Transform the quaternions Q_1 and Q_2 to rotation matrices. And transform the compounded matrix back to quaternion Q_0. This part should be eliminated properly from the result obtained by direct attitude calculation from measurements of these two sensors in working phase.

We have $g_1 = g_0 * R_1$ and $g_2 = g_0 * R_2$

Then $g_1 = g_2 * R_2^{-1} * R_1 = g_2 * R_2^{T} * R_1$

And transform $R_2^{-1} * R_1$ back to Q_0.

So the target rotation is encoded as $Q_1 * Q_0^{-1} * Q_2^{-1}$.

2) Locate the sensors in the right location based on kinematic knowledge. We followed the approach described in previous studies [80, 169], shifting sensor locations from the chest to the back, on vertebrae T1 and T5 in the 2nd iteration for the monitoring of compensatory movement from trunk. After that we followed the ISB recommendations in the later iterations.

3) Keep the sensors in the right location using flexible and scalable mechanisms. We adopted a two-piece design for the garment in our 2nd and 3rd iteration. Velcro applied on the overlap areas made the garment adjustable for people of different sizes and could guarantee the sensors' fixation [76]. However, this solution was not easy to put on and take off (wearability lens). We decided to provide multiple sizes

for Zishi instead of the solution one-fit-all approach. In the 4th iteration, we proposed a new fit & fix method for the shoulder sensor, details about addressing wearability are described in the following section.

3.5.4 Lens of Wearability

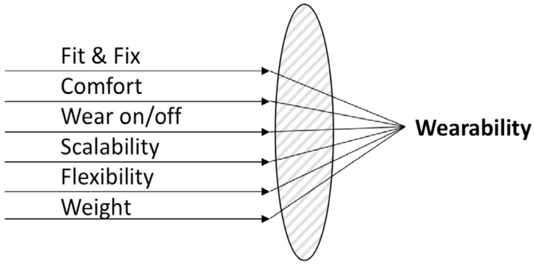


Figure 3.28 Lens of Wearability

Smart garments are expected to enhance the functionality of everyday clothing while still being comfortable, presentable and easy to take on and off and more generally to satisfy wearability requirements. Gemperle et al. [134] defined wearability as the interaction between human body and wearable objects for wearable technology. Various studies [34, 170] argued for the importance of taking wearability into account and even proposed related requirements or principles. This lens (see Figure 3.28) challenges the designer to balance fixation and comfort.

Fit and fix means that the garment should fit the body and ensure the sensors' steady fixation at the right position even during big movements. Common ways to keep sensors at the right location are: snaps, Velcro straps, belts, knitted textiles, stretch materials or specific mechanisms such as foldable structures or an inflatable fixture. Flat body parts that do not move or flex a lot are conducive to stable monitoring. Fit and fix could also help avoid the effect of clothes wrinkle. The style and structure of the garment have direct impacts on the sensor function [58]. For example, Dunne et al. [58] evaluated the variables of garment style and fit through a process of amalgamating possible movements and generated new design constraints to their final design

Comfort may concern the degree of comfort from multiple aspects, such as physical, mental and social. Dunne et al. [171] identifies a number of factors that influence clothing comfort, including pressure/

constriction, texture, thermal, moisture and freedom of movement. The process of fabric selection and prototype implementation can be crucial in ensuring an unobtrusive design with suitable material and attachment methods.

Ease of use refers to several aspects of daily use. The garment should be easy to wear on/off and easy to attach and remove the non-washable parts. Scalability means that the system should support size variations to fit users in different types or in different scenarios. The analysis by Griffin et al. [172] illustrated the need to consider non-traditional sizing strategies for sensorized garments to ensure precise sensor placement. An emerging approach that is very promising is body scanning and computer aided fabrication customized to the body of the user. Flexibility, light weight and adaptability of the garment are different ways to avoid restricting body movements.

Applying the lens of wearability

This lens has been applied throughout our iterations:

1) Figure 3.29 illustrates our gradual progression towards ensuring wearability throughout our iterations. We have strived that *Zishi* could be easily put on and off while balancing other requirements, or that users could wear *Zishi* as daily clothing. Figure 3.29 shows the prototype from the 5th iteration, where we integrated a magnet zipper on the front part of the garment, ensuring that *Zishi* would be easy to put on for patients with diminished motor control. The magnetic zipper is self-closing requiring the user to just bring the two sides of the jacket close to each other, with rather than having to zip up

Figure 3.29 (left) Thumbnails embodied the wearability progress; (right) A model was wearing Zishi easily and was pleased with the smooth experience.

2) Lessons learned about the fit and fix in *Zishi*. Figure 3.30 illustrates two examples of sensor fixation in our process. On the upside, snap buttons (see Figure 3.30a) allow for the soft sensor module to be easily removed or reinstalled, which is particularly convenient for personalizing the sensor modules' number or position or for washing the garment. However, we also noticed some downsides. When trying out the garment we found that the wrinkles under the snap button base hindered sensor performance during training exercises. We then opted for Velcro (see Figure 3.30b) on the shoulder to fix the sensor on the acromion. In the 5th iteration of *Zishi*, aiming for simple and intuitive use, zipper magnets were applied on the shoulder too. A tiny magnet (3mm in diameter) is concealed in each of the small golden square fabrics (see Figure 3.18). In this way, the connection is easy,

(a) (b)

Figure 3.30 Fixation examples in *Zishi*. (a) The soft sensor module (in black colour) can be buckled on the garment by snap fastener; (b) Stretch fabric and Velcro, a soft elastic Velcro strip goes under the two openings of garment, maximize the flexibility and stability.

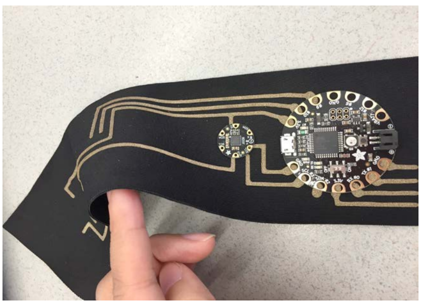


Figure 3.31 Flexible circuit

robust and smooth.

3) Sewable modules or miniature modules were implemented with a flexible circuit (see Figure 3.31). A removable design of the wearable electronics, potentially allows users to have garments made of different materials that would be appropriate for different training applications. Further, all the fabric samples used in our prototypes were elastic and soft. In this way, users would feel comfort with no constraints.

3.5.5 Lens of Aesthetics

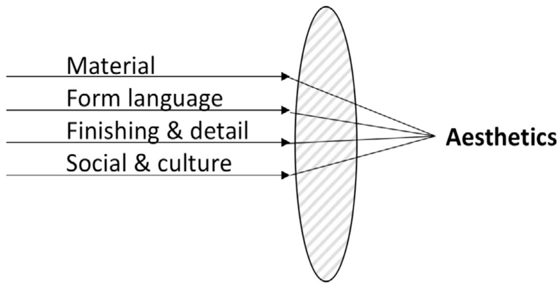


Figure 3.32 Lens of Aesthetics

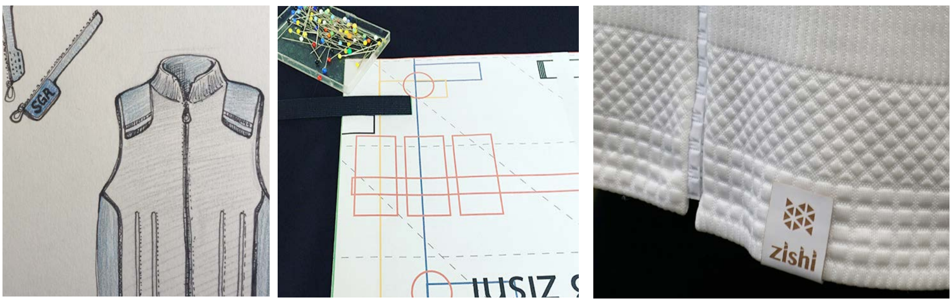
This lens takes the perspective of aesthetics which are often ignored in the field of wearable rehabilitation technology. Aesthetics are crucial for system acceptance to the point that they can determine its final success [158]. Andreoni et al. argued that aesthetics are together with function and technology the three main requirements for designing smart garments [158]. Designing the system not only for rehabilitation but also to allow self-expression, the lens of aesthetic (see Figure 3.32) calls for balancing factors such as: material, form language, finishing & detail and influences from social & cultural, etc.

The selection of material including textile and fiber, their structures and properties will influence the cutting pattern and finishing. We list three main considerations: a) Colour and texture selection may reflect fashion design, user preferences, culture, etc. Advances in smart fiber (e.g. led fiber and photonic band gap fiber (Karma Chameleon project [173]) and thermochromic inks, dynamic textile colour and pattern are all innovations that have been applied recently in smart garment, creating new ways of colour experience. b) Considering the factors "fit & fixation" and "comfort" in the lens of wearability, various soft, stretchable and breathable textiles can be employed. c) The intended environment and seasonal requirements should also be considered during fabric selection.

The factor "Form language" refers to shape and styling. It is essential to consider the body in terms of 3D form in the process of sketching, illustrating technical drawings and paper prototype on the tailor's manikin. Ensuring that both design and cutting lines work in harmony may lead to clean and minimal styling [174]. It is a challenge to naturally merge hard electronics into the textile, instead of casually fixing them at some point.

The high quality of finishing in fabrication, cut, proportion and detail (e.g. logo) will contribute to the 'feel good' factor. Designers can follow the fashion design process to design the pattern-cutting, tailor, stitch and work with new techniques such as laser cutters, 3D printer, computerized knitting machines and embroidery machines. Some design details such as the clothing labels, zip openings, clean garment edges may contribute unforeseen enhancements.

It is also important to focus on social and cultural influences. Wearing the smart garment may lead to people perceptions like "high-tech". On the other hand, users may also feel embarrassed and concerned that they will be labelled as "strange". Pervasive smart garments rely on users wearing the system over the long-term, in daily contexts, which relies heavily on wearer's emotional and social comfort.

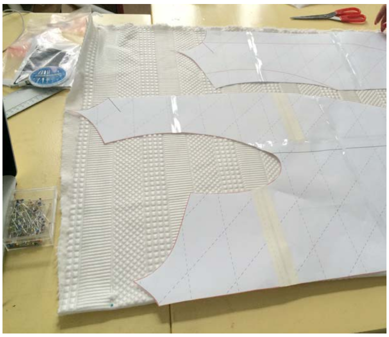


(a) (b) (c)

Figure 3.33 (a) sketch in the 3rd iteration; (b) pattern design in the 6th iteration; (c) zoom-in figure shows the label, texture of the fabric and finishing detail in the 5th iteration.

Applying the lens of aesthetics

(a)

(b) (c) (d)

Figure 3.34 design progress. (a) the back part design of the final prototype in 5th iteration; (b) embryonic form with pins fixed the fabric on a manikin; (c) tailoring; (d) testing the patch

Figure 3.33 presents some examples of our general design process (e.g. sketches and pattern design) considering the lens of aesthetics. The interactive garment was designed with aims to look friendly and familiar in order to offer better engagement.

Figure 3.34 illustrates an example towards the form language by showing the back design of *Zishi* in 5th iteration and the design process. The flexible central node could fit in the concave space by the magnet zipper, thus achieving an integral surface. From the aesthetic perspective, we created a feeling that when the sensing part is attached the garment is a whole piece that is not obtrusive. We aimed to design the structure of the clothes, not simply add on devices.

3.5.6 Lens of Interactivity

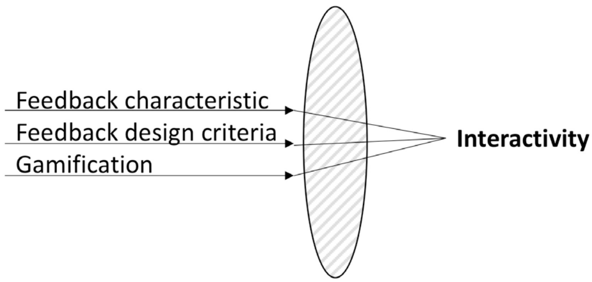


Figure 3.35 Lens of Interactivity

This lens (see Figure 3.35) focuses on the interactive guidance a smart garment can offer to patients and the emerging user experience. Particularly, it is of major importance to design the system feedback as this positively influences motivation and self-efficacy [11]. Wearable systems raise questions about the interactive experience grounded in the body, give both physical and virtual dimension to interaction. This lens considers the characteristics of feedback, interaction design principles regarding feedback design or even gamification as a potential approach. This lens challenges designers to think how to provide accurate, reliable, understandable and pleasurable feedback.

It is important that feedback matches the proficiency level of the users [11], which determined by the modality, contents and timing [95], their characteristics are summarized as follows:

1) Content: program and parameter feedback provides information towards movement pattern, summary feedback and average feedback due to the amount of information, bandwidth feedback based on a custom threshold for error magnitude and focus of attention. Feedback strategies could be established based on underpinning theories [10] and real contexts.

2) Modality: visual, auditory, haptic or multi-modal feedbacks.

3) Timing: terminal and concurrent feedback, the frequency of feedback provision.

In Chapter 2, we have discussed extensively the feedback mechanisms supported by wearable rehabilitation technology. However, the transition from a technical tool towards a clinically usable system is not straightforward. Prerequisites for therapists and patients to use technology supported rehabilitation systems are the ease-of-use of the system, its added value to their habitual rehabilitation programs and its credibility. There have been several attempts by researchers to distill related design guidance. Willems et al. [175] identified a set of guidelines for patient feedback design in stroke rehabilitation technology. Hochstenbach-Waelen and Seele [163]inventoried criteria technology should meet, multiple items towards feedback and software have been explained. Timmermans et al. proposed criteria related to feedback on exercise performance. Designers and researchers are also recommended to draw lessons from the classical principles, for example, Jakob Nielsen's ten heuristic principles [176].

Besides, a game may increase both the quality and quantity of patients' training by providing a motivating context and decreasing the monotony of repeated motions [36]. Numerous studies argued that gamification design feedback contributes crucially to achieving effective engagement [36, 80, 177]

Applying the lens of interactivity

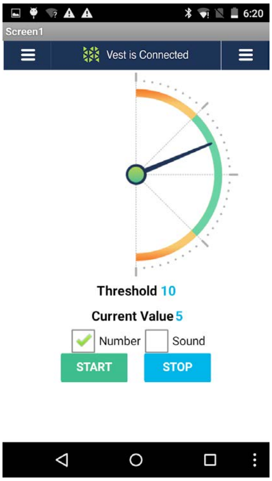


Figure 3.36 interface design

By applying the lens of interactivity, *Zishi* was accompanied with the real-time application including on-body vibration feedback and visual and sound feedback from the app (see figure 3.36). Besides, the following lessons were learnt:

1) Real-time feedback is essential, which is known to be effective for beginning users [11]. Since we target motor-control training, real-time feedback helps users achieve self-awareness of their movement performance. We used green and red colours to indicate user their concurrent status so that they are informed whether their posture is in the acceptable range.

2) The application on smart devices should be easy to understand and operate; the design should avoid information overflow. For example, our initial design provided compensation data for torso and shoulder concurrently as both values are relevant. However, users got confused as tracking the two parameters put excessive demands on their attention.

3) Personalization and adaptivity. To support goal setting by patients and to apply the device in diverse situations, personalization and adaptivity are vital. *Zishi* supported personalization by registering the user's neutral position and allowing them to personalize thresholds. The feedback modalities are also personalized as users could enable

or disable the modality by checkbox anytime. For beginners, simple feedback may prevent information overload, for experienced users, more elaborate feedback may enhance the system applicability.

4) Towards motivational aspects, engaging feedback strategy should be nicely presented by the graphical user interfaces. We adopted the pointer to simulate user's movement in a clear and natural way.

3.5.7 Lens of Hard & Soft crafting

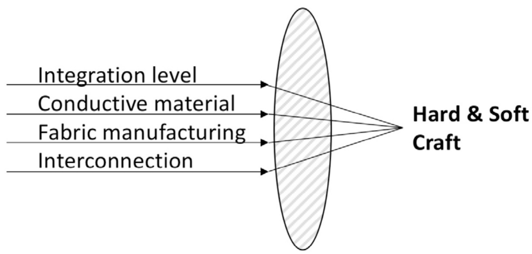


Figure 3.37 Lens of Hard & Soft crafting

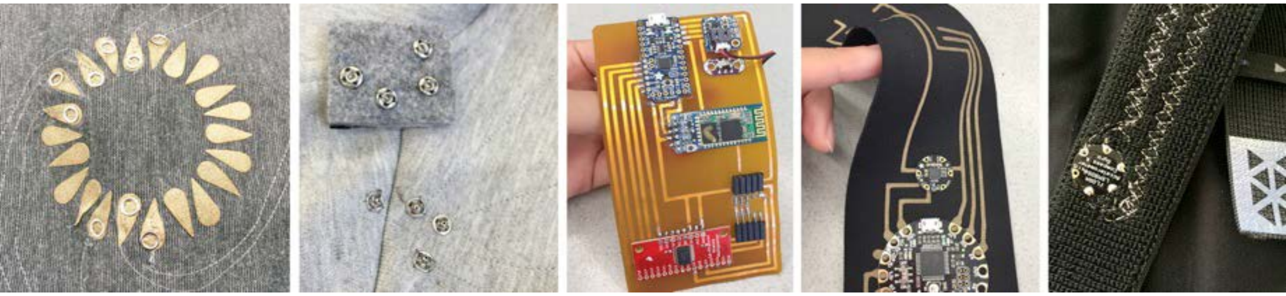
Hard and soft connection is one of the most paradoxical problems in wearable prototypes, it pertains to the balance between accuracy and wearability. This lens (see Figure 3.37) takes the perspective of garment implementation, addressing a set of very practical concerns. The integration between electronic modules and a textile substrate can be classified into three levels as explained in Chapter 2 (i.e. attached, embedded and integrated).

Conductive materials are essential for reliable joining electrical modules and textile. The conductive material consists of conductive threads/yarns, conductive fabric and conductive ink. Andreoni et al. [158] classified yarns in two categories of metal yarns (e.g. stainless steel) and yarns containing electro-conductive fibers (e.g. carbon-coated threads). Locher et al. [178] have listed different types of conductive yarns including plain wire, twisted yarn, tinsel, plated yarn, plated strips and double twisted yarns. Pre-tests of their properties (e.g. resistance) are essential before integrating the material.

Previous studies [160, 178] have concluded different ways of incorporating smart materials into the textile structure by different manufacturing and treatment technologies including: embroidering, sewing, non-woven textile, knitting, weaving, spinning, braiding, coating/laminating, printing and chemical treatments. Previous E-textile summer camp [179] and Kobakant et al. [180] have demonstrated copious hands-on E-textile solutions and inspirations on their website. Frequently used approaches are listed as following: 1) soldering and welding; 2) sewing and embroidering; 3) sealing and isolating; 4) adhesive bonding; 5) hook & loop; 6) magnet and snaps; 7) IDC connector, etc.

Applying the lens of Hard & Soft crafting.

Appropriate interconnection mechanisms and connection procedures are crucial ingredients for crafting smart garments. Figure 3.38 illustrates some examples of the different connections we used in the design iterations. We applied different approaches because of the different material properties, while ensuring the good function of the electronics as well as the flexibility and robustness of textiles [178]. For example, the polyester conductive thread was fixed on conductive fabric with a pronged cap in the 2nd iteration. However, the resistance of the whole system turned out to be quite high because the selected yarn and the tailored tool for the pronged cap were hard to operate when the target was far from the fabric edge. However, since the resistance of the adopted conductive yarn was quite high, the system was not stable enough to support tests with users.



(a) (b) (c) (d) (e)

Figure 3.38 Explorations of connections in the different iterations. (a) Polyester conductive thread and fabric with pronged cap; (b) Stainless conductive thread with snaps embedded in the garment; (c) Electronic modules mounted on the flexible PCB; (d) Laser cutting the conductive fabric pattern and transfer to the substrate fabric by heat-press machine; (e) Coated conductive thread sewed and soldered with the sensor.

3.6 Conclusions

This chapter has recounted the iterative design progress of developing the interactive garment, described the system overview and proposed design lenses towards different perspectives while designing smart posture monitoring garments for rehabilitation.

We set out to design a garment as a platform for arm-hand rehabilitation. We have proposed a design of the smart rehabilitation garment system, providing feedback on compensation movement to improve users' correct execution of exercise. The integration of smart textiles design to wearable systems contributes to implementing the reliability and comfort of posture monitoring systems. The system can be used in different context and training approaches and the adjustable design ensures the sensors stay in the right positions. Due to the modular and cost-effective design, the system has a good potential for accuracy and comfort.

The six lenses presented, have been articulated in order to guide interaction designers and researchers who are interested in designing developing interactive smart garments for rehabilitation. The development of interactive rehabilitation technologies attracts researchers from different backgrounds such as biomedical science, engineering, rehabilitation, computer science and design as an interdisciplinary field. Our explorations have encoded some different perspectives that designers and researchers can focus on while designing and developing interactive posture monitoring garments for rehabilitation. Taking different lenses and frequently shifting between them is necessary to take into consideration of diverse perspectives and manage diverse requirements. Lenses help focus on a specific part while taking into account the overall design goal. There may well be some overlap contents of several lenses (e.g. factor "fit & fixation" and factor "form language"), on the other hand, switching between lenses can help designers to approach designing wearables for rehabilitation from different perspectives [151]. The design narrows down on key design considerations and specific factors that may provide valuable guidance to researchers, designers and engineers new to this hybrid area. In the future, we will explore how the lenses may be employed in future wearable system development and the community could leverage the knowledge.

4

Zishi: Evaluations

This chapter is based on:

1.Q. Wang, L. De Baets, A. Timmermans, W. Chen, L. Giacolini, T. Matheve, and P. Markopoulos, “Motor Control Training for the Shoulder with Smart Garments”, Sensors, vol. 17, no. 7, pp. 1687–18, Jul. 2017, DOI: 10.3390/s17071687.

2. Q. Wang, W. Chen, A. Timmermans, C. Karachristos, J.B. Martens, P. Markopoulos, “Smart Rehabilitation Garment for Posture Monitoring” in 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Milan,2015, DOI: 10.1109/EMBC.2015.7319695;

3. Q. Wang, A. Timmermans, W. Chen, J. Jia, L. Ding, L. Xiong, J. Rong, P. Markopoulos, “Stroke Patients’ Acceptance of a Smart Garment for SupportingUpper Extremity Rehabilitation”, Journal of Translational Engineering in Health and Medicine (current status: accepted).

My contributions to these papers are in the conception, prototype design and development, implementation, execution of the evaluation of Zishi, data analysis, as well as in writing the paper.

4.1 Introduction

Chapter 3 presented the design and development of *Zishi*, as an iterative design process, both the act of designing and the act of evaluating designs are essential. In Chapter 2, we distinguished three different kinds of evaluation: technical evaluation, usability evaluation and clinical evaluation. Our systems have been deployed in the lab test and real context for different target users. A pilot study was set up to evaluate the accuracy performance (with the 3rd iteration). Two studies (with the 4th iteration) have been conducted exploring about users' attitude towards system credibility and expectancy, intrinsic motivation, technology acceptance and usability. We recruited shoulder pain patients and therapists in Hasselt, Belgium and stroke patients and therapists in Shanghai, China.

4.2 Accuracy Evaluation

With the third iteration of *Zishi*, a pilot study was set up and administered in order to evaluate the performance of the garment for measuring the thoracic angle. We compared Zishi to a commercial optical tracker (PST-55/110 series) that uses infrared lighting to detect optical markers from ps-tech (see www.ps-tech.com). Experiment data are presented by the mean value, standard deviation, and root mean squared errors (RMSE). Written consent was acquired from each participant prior to the experimental sessions. This was a non-clinical study without any harming procedure and all data were collected anonymously. Only healthy participants were involved to register simple motions in a non-invasive way, and without collecting any personal data on the participants. Therefore, according to the Netherlands Code of Conduct for Scientific Practice, ethical approval was not sought for the execution of this study.

4.2.1 Experiment setup

By using the 3D motion capture system one L shaped hard piece with two optical markers was attached to each sensor. The raw data provided by the system are the space coordinates and we calculate the angles between two space vectors by applying the calculation model. Seven subjects without any related pathology (4 female and 3 male) participated in this experiment. After putting on the garment they

Figure 4.1 Experiment Setting, subject stood in front of the optical tracker with two infrared markers attached to each sensor.

were introduced to how to interact with the application to control the prototype wearable system . Then participants were asked to stand in a marked position in front of the optical tracker. Figure 4.1 shows the experiment setup. The experiment procedure is as follows: 1) stand straight with feet flat on floor, keep still (last for approximately 2 seconds to implement the calibration process) then click button on smartphone to set personalized "0" as the starting position; 2) bend forward until the App displays 15° and keep still; 3) bend forward further to 30°, 45°, 60° and 75° separately. 4) The subjects repeated the exercise series three times, for every target angle in random order. While the participants stood still, the observer recorded the data with the optical tracker.

4.2.2 Results

Table 4.1 Evaluation Results

Angles	15	30	45	60	75
MEAN	17.45	33.39	48.27	63.47	79.08
RMSE	2.61	3.66	3.71	3.79	4.56
SD	1.14	1.29	1.97	1.62	1.93

Table 4.1 presents the average RMSE (root mean squared error) and standard deviation results. The average value of the three times measurements from 7 subjects are illustrated in Figure 4.2. The RMSE increases with the flexion angle. The reason may be that the sensor is placed in loose contact with the skin, so the alignment of the sensor to

the body shifts slightly when the angle increases. The RMSE presents the average deviation extent, and the global RMSE value is 3.57. The accuracy achieved is comparable to the state of the art in wearable technologies (as shown in our survey [21] and the systematic survey of chapter 2), while arguably improving on aesthetics and wearability substantially.

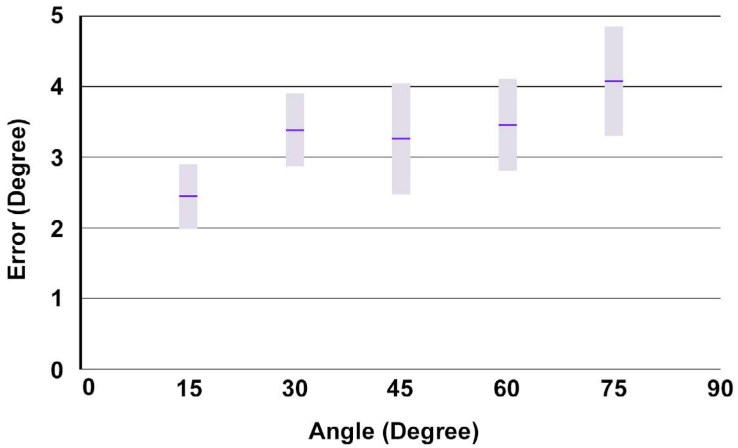


Figure 4.2 Mean Value and Standard Deviation

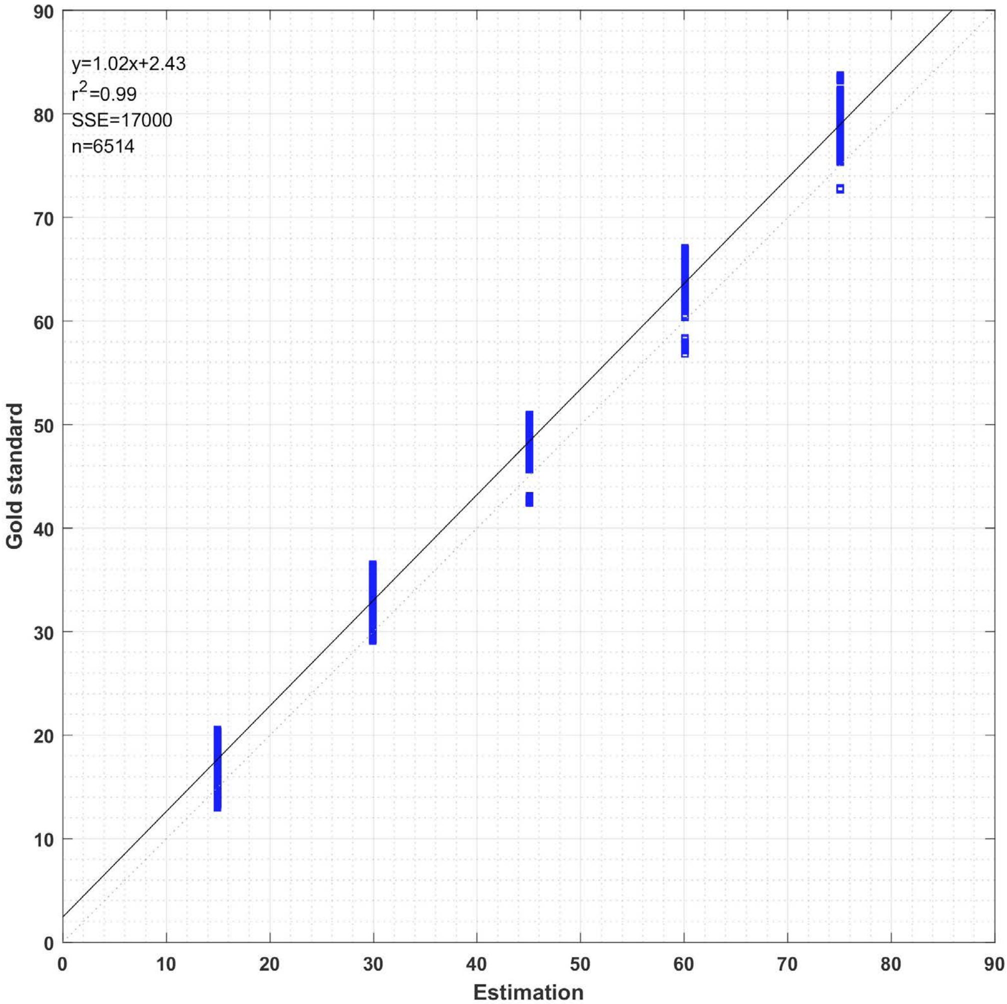


Figure 4.3 Linear regression analysis

Figure 4.3 demonstrates the single linear regression analysis, a significant regression equation was found (F(1,6512)=9,74e+05,p<0.000), with an $R^2$of 0.993. The gold standard value (data from optical system) could be predicted as 2.43 + 1.02 (data from Zishi system).

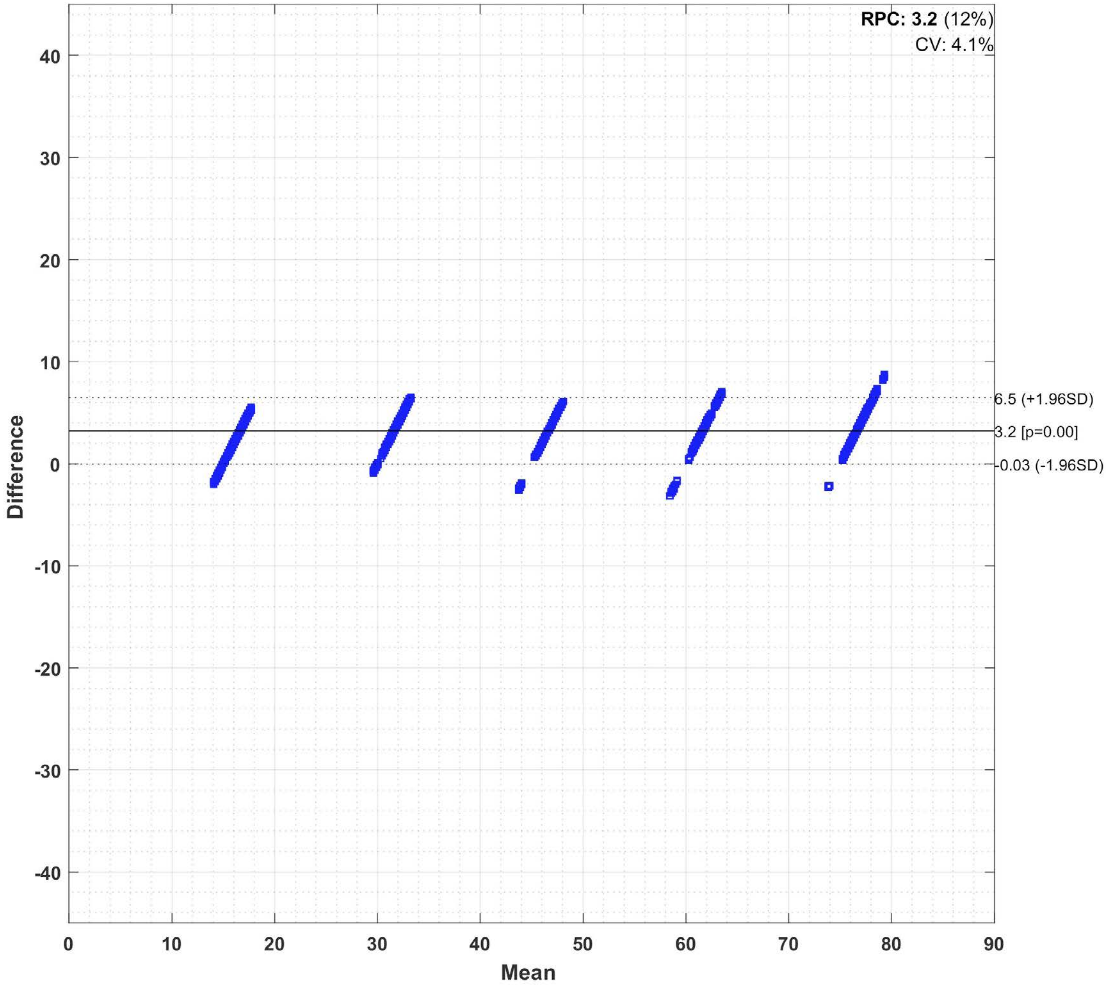


Figure 4.4 Bland and Altman analysis

In order to assess agreement between two methods of measurement, we also performed the Bland and Altman analysis[181, 182]. Figure 4.4 demonstrates the analysis results which confirmed the acceptable deviation between the two methods (bias = 3.2 and and the 95% limits of agreement are 6.5 and -0.03) .

4.3 Motor control training for the shoulder with smart garments

4.3.1 Introduction

Shoulder problems are very common. In reaction to pain or in order to unload painful structures, patients tend to develop altered movement patterns which can be seen as compensatory movements [13]. Thus, rehabilitation treatment should involve correct positioning of the scapulothoracic joint scapula on the thorax by means of active muscle recruitment and re-education. Patients need to learn an optimal scapular orientation in relation to the thorax. Currently patients learn such a 'scapular setting' referring to an instruction manual, or by relying on verbal and auditory assistance by their therapist [183].

Posture monitoring technology can help detect and subsequently reduce the compensatory movement patterns of the scapula on the thorax in several ways. First, it can support the patient in executing scapular setting exercises by providing objective feedback on the scapular setting and trunk position which can contribute to the effectiveness of the training. Secondly, it can be supportive for therapists, since it can be an addition to the manual/verbal/auditory assistance they provide to patients. Lastly, it provides continuous and objective feedback, which can potentially improve the quality of the training. However, before a technical measurement or rehabilitation tool can be clinically applied, information about the ease of use of the system [27] and attitudes by users towards this technology is required.

The aim of this study is to evaluate users' attitudes regarding the usability, credibility, acceptance, and motivational aspects of technology-supported postural feedback during scapular training in patients with musculoskeletal shoulder pain and in physical therapists who treat patients with shoulder disorders. The study received ethics clearance from the ethics boards of Jessa hospital (Hasselt, Belgium) and Hasselt University. The study comprised of two parts; in the first part patients were asked to use Zishi while executing scapular setting exercises and in the second part, physical therapists tried out Zishi themselves and evaluated the system as a therapy aid.

4.3.2 Participants

Eight patients with musculoskeletal shoulder pain receiving rehabilitation training and five physiotherapists from the rehabilitation center of Jessa hospital were recruited and signed the informed consent before the study. Eight patients with pain from musculoskeletal origin (five females and three males) agreed to participate in our study. Their ages ranged from 45 to 59 years (M=50, SD=6.44) and they had been following shoulder rehabilitation training for 9.7 months on average (SD = 5.8) and their mean SPADI score was 45.3 (SD = 15.3%).

The inclusion criteria for the shoulder patients were: 1) main complaints at shoulder girdle; 2) older than 18 years of age; 3) presence of at least one of the following signs: positive Neer test, positive Hawkins-Kennedy impingement, painful arc during active abduction/flexion, pain during one or more of following movements: external rotation/ internal rotation/ abduction/ flexion; 4) understanding spoken and written Dutch.

The exclusion criteria were: 1) Surgery at the shoulder complex or cervical spine in last 6 weeks, 2) comorbidity: paresis and sensory problems of neurological origin/diabetes mellitus/rheumatoid arthritis, pain severity 8/10 or more in the last 48h, adhesive capsulitis/frozen shoulder, 3) having any insurance compensation claims in progress.

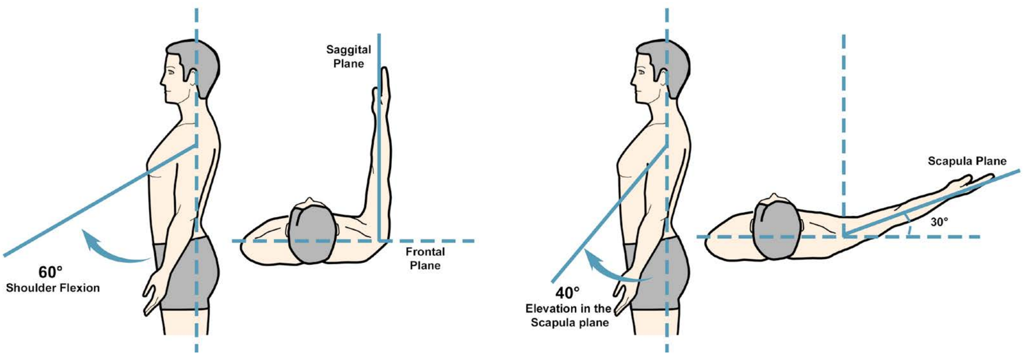
4.3.3 Materials

Zishi was made available in two sizes. The materials for the experiment also included an Android-based tablet with the App installed, an adjustable shelf, a cooking pot (weight 300g, size 6 inches) and a bottle of water (0.5l). Although *Zishi* is capable of providing feedback in 3 different modalities, only visual and audio channels were enabled during the experiment to prevent information overload (vibrotactile feedback was disabled).

4.3.4 Protocol

Based on discussions with therapists, it was decided to only focus on the right part (shoulder girdle feedback) of the interface to avoid that concurrent feedback on two different aspects of posture (i.e. from the trunk and the shoulder girdle) would be too difficult for patients to handle given that they were not yet familiar with the system and its feedback. Before starting the experiment each participant filled in two pre-test questionnaires: a socio-demographic questionnaire (name, date of birth, gender, height, weight, contact information, shoulder pain suffering time and position, handedness and whether they had surgery on shoulder) and the Shoulder Pain and Disability Index (SPADI) questionnaire [27], a self-administered inventory to gauge the shoulder pain they experience at the moment and the disability of shoulder functioning. The SPADI questionnaire generates a score ranging between 0-100, reflecting the amount of disability of a person, with higher scores corresponding to a higher degree of disability. Researchers, who are also musculoskeletal physiotherapists, demonstrated *Zishi* to the participants and explained its operation and interface contents. Subsequently, the participant put on the garment and ran through the calibration procedure. All tasks were performed in a standing position, with help from a researcher where necessary. During task-execution, the patient was instructed to stabilize the scapula on the thorax and avoid inappropriate scapular elevation or depression. The neutral scapular position was calibrated and the threshold for allowed compensatory movement was set at 10° of scapular elevation or depression.

Test participants were asked to perform the following tasks:



(a) (b)

Figure 4.5 Movement description: (a) Shoulder flexion; (b)Elevation in scapula plane.

(a) (b)

Figure 4.6 Task Execution: (a) Standardized calibration of arm movement with goniometer; (b) The subject is performing task 4, lifting the bottle to the board.

1) Task 1: analytical shoulder flexion. The subject was asked to perform 60° of shoulder flexion with the thumb up and the elbow extended (see Figure 4.5a). A bar was placed in front of the patient at 60° to indicate the appropriate level of flexion. The range was determined with a goniometer, as shown in Figure 4.6a.

2) Task 2: functional shoulder flexion, placing a cooking pot. The subject was asked to place a cooking pot from a plate on a shelf that was located in front of him/her. The height of the shelf and the distance from the patient were standardized. The subject started with his arms alongside his body and with the elbows in 70° of flexion (determined with goniometry). The height of the shelf was adjusted accordingly. The patient had to perform 60° of shoulder flexion with extended arms, to place the pot on the shelf. Once subjects had placed the cooking pot on the shelf, they were asked to put it back on the shelf in front of them.

3) Task 3: analytical elevation in the scapular plane. The subject was asked to perform 40° of shoulder elevation in the scapular plane (30° in front of the frontal plane) with an extended elbow and with the thumb pointing upward (see Figure 4.5b). A bar was placed in the scapular plane, next to the patient at 40° of humerothoracic elevation to indicate the appropriate level of elevation. The range was determined with a goniometer.

4) Task 4: functional elevation in the scapular plane. The patient was asked to place a bottle of water (0.5 l) on a shelf that was located next to

him in the scapular plane. The height of the shelf and the distance from the patient was standardized. At the starting position, the patient had his arms alongside his body and his elbows in 70° of flexion (measured with a goniometer). The bottle was in the hand of the tested arm side. The shelf was placed so that the patient had to perform 40° of scapular plane shoulder elevation with an extended arm to place the bottle on the shelf. Figure 4.6b shows a subject performing task 4.

Five therapists participated in the second part of the study. They performed the same protocol as described above, in order to gain a first-hand experience of the system before providing their own appraisal of it.

At the end of the test sessions, participants were asked to fill in a number of questionnaires that assessed different aspects of the system.

4.3.5 Outcome measures

Credibility and expectancy

To evaluate whether participants think that *Zishi* is a potentially credible aid for treating shoulder pain (credibility), and whether they feel it will facilitate improvement of their condition (expectancy) we asked them to complete the Credibility Expectancy Questionnaire (CEQ [184]). The CEQ includes a credibility factor (to indicate how believable, convincing and logical treatment is) as well as an expectancy factor (expected improvements). In therapists, only the questions related to credibility were asked, as they are not assumed to have a musculoskeletal problem they are treating with the device. The questionnaire consists of 4 questions on what subjects 'think' in section 1 and 2 questions on what subjects 'feel' in section 2, while the factor credibility is derived from the first three thinks questions and factor expectancy is derived from the remaining questions.

Intrinsic motivation

As we assume that interactivity will make exercise more engaging and will increase patient motivation to train, we asked them to fill in the Intrinsic Motivation Inventory (IMI [185]). The full version of IMI consists of 45 questions addressing 7 subscales. Since the subscale 'Perceived Choice' is not relevant for our system, we only focused on the other 6 subscales including 'interest/enjoyment', 'perceived competence', 'effort/importance', 'value/usefulness', 'relatedness' and 'pressure/tension'. The 'interest/enjoyment' subscale is considered as the self-report measure of intrinsic motivation. 'Perceived competence' subscale shows how capable the subjects feel and theorized as predictors of intrinsic motivation. The 'effort/ Importance' and 'pressure/tension' subscales respectively measure subject's effort investment and pressure during the task performance. The subscale 'value/usefulness' aims to capture the extent to which people internalize and develop more self-regulatory activities when experience is considered as valuable and useful for them [185]. Questions in the subscale 'relatedness' are designed to reflect the degree of participants' perceptions and expectations of social connection when using the system.

Technology acceptance and usability

To evaluate whether participants would be likely to use such a device, we assessed technology acceptance using 'Unified Theory of Acceptance and Use of Technology' (UTAUT [186]). Developed in the field of information systems management, the UTAUT inventory measures variety of factors that are known to predict use of technology. However, UTAUT is not very explicit about system usability, which is an important concern for interaction design. For this reason participants were also asked to complete the Computer System Usability Questionnaire (CSUQ[187]) developed by IBM which is a short, reliable, and widely used questionnaire for assessing system's usability. The CSUQ questionnaire consists of 19 items for measuring user satisfaction with four perceptions of satisfaction: overall satisfaction (Q1-Q19), system usefulness (Q1-Q8), interface quality (Q16-Q18) and information quality (Q9-Q15). Finally, we also asked several questions addressing the general experience and quick impression of the system usability: two rating questions (R1-"How easy can you understand the feedback?"; R2-"How easy was it to take the vest on and off?") and two open questions (O1-"What do you like about the system?"; O2-"What would you change about the system?").

Credibility and expectancy for therapists

The therapists filled in the credibility component only of the CEQ questionnaire. Furthermore, to assess the general impression and usability, and to receive suggestions for improvement of the interface design, several open questions were asked (for example, "What do you think about the arrow - was it clear? Should you replace it by an avatar? Or by an image of yourself?" To learn about therapists' opinions about the feedback strategy, we asked the questions: "Do you prefer feedback during or after the exercise?" and "Do you prefer feedback about the manner of movement (knowledge of performance) or only on the result of movement (knowledge of results)?".

4.3.6 Results of patients' evaluation

Table 1 presents the group Median, IQR scores and one-sample Wilcoxon signed rank test results of the different questionnaires and their subscales. Scores range from 1-7 for all factors apart from credibility and expectancy which range between 3 and 27. Abbreviations: IQR = Interquartile Range, Sig = Significance level of Wilcoxon Signed-Rank Test for One Sample, comparing to the neutral score of each scale.

Measurement results of credibility and expectancy

Patients scored highly both the credibility and the expectancy (see Table 4.2) as both scores were higher than the neutral score of 13.5 (credibility Median= 22.5, p = 0.011, IQR= 3.5; expectancy Median= 20.2, IQR= 3.55 ; p = 0.012).

Table 4.2. Overview of system scores.

Factor		Median(IQR)	Sig
Credibility/ Expectancy (CEQ)	Credibility	22.5 (3.5)	0.011
	Expectancy	20.2 (3.55)	0.012
Intrinsic Motivation (IMI)	Interest/Enjoyment	6.43 (0.82)	0.012
	Perceived competence	5.25 (1.96)	0.028
	Effort/Importance	5.8 (1.9)	0.025
	Value /Usefulness	5.93 (1.93)	0.012
	Relatedness	5.6 (2.05)	0.012
	Pressure/Tension	2.2 (2)	0.025
Technology Acceptance (UTAUT)	Performance expectancy	5.37 (1.75)	0.018
	Behavioral Intention	5.67 (1.58)	0.058
	Attitude towards technology	5.3 (0.85)	0.012
	Self-Efficacy	5.25 (1.19)	0.16
	Effort expectancy	5.62 (1)	0.011
	Facilitating conditions	5.25 (1.44)	0.024
Usability (CSUQ)	System usefulness	5.63 (1.53)	0.012
	Interface quality	5.67 (1.33)	0.011

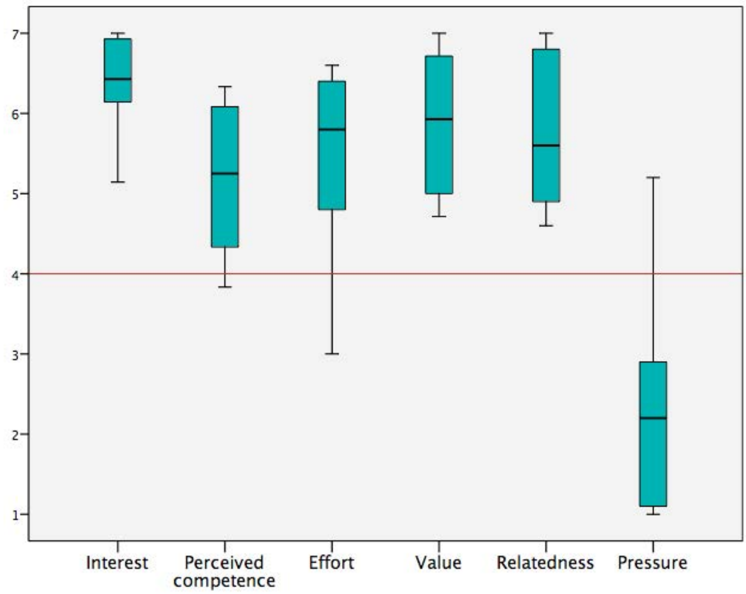


Figure 4.7 Subscale findings of the Intrinsic Motivation Inventory questionnaire evaluated in patients with shoulder pain.

Measurement results of intrinsic motivation

Figure 4.7 illustrates shows that scores given for the six subscales of the IMI questionnaire. For all subscales, patients scored well above the neutral score of 4 (see also table 1), with the exception of the subscale 'pressure/tension' which is a negative predictor ("*less pressure is better*") and should be ideally below the neutral. The 'interest/enjoyment' subscale which is considered the most direct self-report measure of intrinsic motivation, indicated that the subjects were more than neutral motivated to use the system significantly (Median=6.43, IQR=0.82; p=0.012). The 'perceived competence' and 'effort/importance' subscales resulted in acceptable scores and the 'value/usefulness' and 'relatedness' subscales were scored highly. The low score of subscale 'pressure/tension' showed that subjects did not experience pressure or tension during the task.

Technology acceptance and usability

We use UTAUT to assess the constructs that influence technology acceptance (Behavioral intention) and use (Behavior) of the *Zishi*

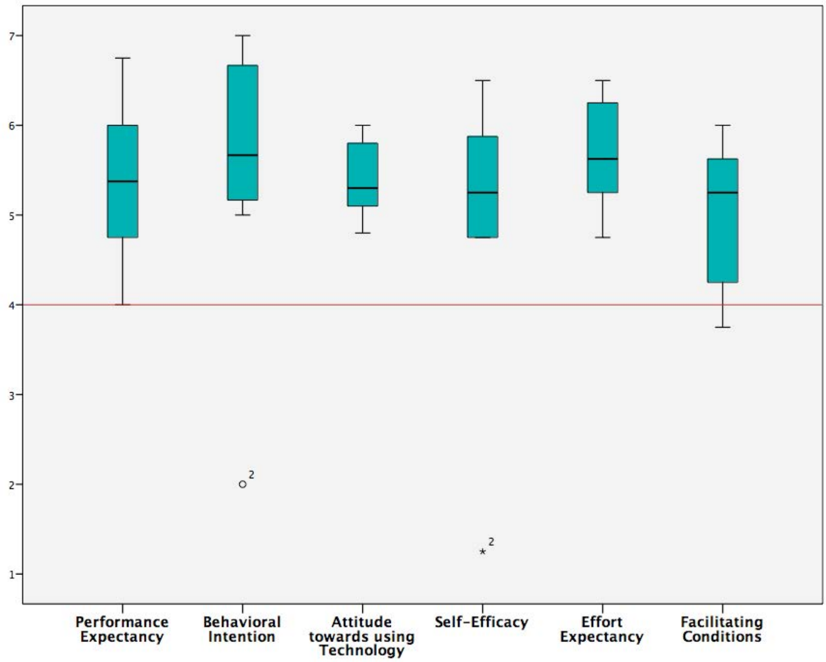


Figure 4.8 Technology acceptance was measured with the UTAUT questionnaire, achieving positive evaluations by the participants.

system. The results (see Figure 4.8) indicate that the subjects believed that *Zishi* may help them (Performance expectancy) and they expect that it will require little effort to use (Effort expectancy). In general, patients were positive towards using the *Zishi* for training their shoulder, reporting high scores on the behavioral intent scales (Behavioral intention), rated positively contextual factors that would influence their ability to use the *Zishi* (Facilitating conditions) which suggests that they believe that the technology could be integrated in the current treatment practice. For the subscales of Behavioral Intention and Self-Efficacy participants did not rate significantly higher than the neutral point of the scale. However, at closer inspection this result can be exclusively attributed to one participant scoring at the opposite side of the scale than all other participants, perhaps because of a misinterpretation of the scale. If this outlier is removed, then also these scores are found to be significantly higher than neutral ($p=0.018$ for both subscales).

Table 4.2 shows that system usefulness and interface quality were both rated very high. Overall, the results indicate the high appreciation and good usability since the questionnaire comprises questions on the ease of use, ease of task completion, ease to understand and learn, and interface comprehension. However, three subjects found it difficult to understand and answer items Q11, Q12 and Q15, so we didn't report subscale information quality and overall satisfaction. While it is noteworthy that (Q13-"*The information provided by the system is easy can you understand the feedback*") was rated positively (Median=10, IQR =1.75, in a scale of 10).

In addition, the garment was found easy to take on and off (Median=10, IQR =1.75). Regarding to the first open question (O1-"what do you like about the system"), only 5 subjects responded. They said that *Zishi* is good for their training because of the correct, direct and understandable feedback. One subject even mentioned that she will recommend it to other shoulder pain patients, while two subjects mentioned that the app did not seem easy to use at home for older people. Only one subject replied to the second open question (O2-"what would you change about the system") requesting to make the pointer sharper.

4.3.7 Results of therapists' attitudes

The 5 therapists gave credibility accreditation (Median = 20, IQR= 5.5), which indicates that therapists find the system credible for shoulder pain rehabilitation. Concerning the open questions, 3 therapists agree with the current design, while 2 therapists propose that replacing the arrow by an avatar would increase motivation. All therapists indicated that providing concurrent feedback about the movement is essential. Three therapists stated that both concurrent feedback and end of session feedback would be appropriate. On the question "How do you want patients to receive feedback?" all therapists missed a summary of the performance progression and would like a control to choose which feedback is shown to the patient (torso or shoulder). The therapists complained about having to hold the tablet during training requiring a stand on which to place the tablet during training. The positive aspects were summarized as follows: "Useful, user friendly, easy and no preparation time, can motivate patients."

4.3.8 Discussion

Evaluation of patient attitudes towards the prototype reveal a very positive perception of the system concept. *Zishi* is perceived as credible and usable, while training with the system is overall experienced as motivating. That participants expressed a wish to take *Zishi* home to train is particularly promising. *Zishi* appears to strike a balance between accuracy and comfort, it is easy to use and does not require a lot of space. Compared to wearable sensors that have to be attached to the body with straps or adhesives (e.g., the XSens system), designing the wearable to look like everyday clothing can make it unobtrusive, especially if extra attention is paid to aesthetic/fashion aspects. The wearability of the system enables training daily living tasks as has been demonstrated by the tasks included in the evaluation of our experiment (e.g., placing the cooking pot on a shelf). This ensures the relevance of training to improving the daily life of patients but also the potential to extend scapular setting training at home. Besides, Zishi was perceived as useful and ease of use (short set-up time) by therapists.

The gauge in the *Zishi* interface accompanied by a numeric reading is clear and efficient for simple training tasks. Although it is valuable to monitor compensatory movement from the trunk and shoulder at the same time, the combined dials pose a large cognitive load to patients and for this reason we did not expose participants to both dials at a time, especially because there was not the opportunity for them to familiarize with the system through repeated training sessions.

Half of the participants mentioned their preference and trust in concurrent feedback, which is known to be effective for beginning users [11], since they can correct the posture immediately. Based on the comments form the patients, it appears that the bandwidth feedback strategy has been useful for improving the user's posture awareness. Audio feedback triggered when participants moved out of the training bandwidth is helpful without requiring visual attention during functional tasks.

By using conductive materials such as conductive yarn and textiles *Zishi* supports a reconfigurable and robust connection between the garment and sensing package, ensuring both the wearability and aesthetic quality. The high intrinsic motivation of patients participating in the evaluation, and the positive credibility and acceptance scores indicate that patients are very positive about integrating *Zishi* into their current training. A larger scale study may also be able to explore in more depth potential effects of age, gender, experience and voluntariness of use on the attitudes regarding this technology.

4.3.9 Conclusion

A number of requirements for wearable rehabilitation garments have been addressed in the iterative design and development of the Zishi system. This work illustrates how technology can monitor compensatory movements for supporting a shoulder-training program. The evaluation demonstrates the credibility of the approach, the high usability of the system, and its positive reception by patients and therapists in terms of technology acceptance and motivation to train with the system.

Now that we have knowledge of the feasibility of the system by the end-users in a clinical context, a trial on the clinical effectiveness of the system, in comparison to traditional rehabilitation methods, is the next imperative step. Future studies should examine whether the system is effective in motor learning for shoulder patients, and whether it helps achieve gains the quality and intensity of the rehabilitation. Further, the potential of the device to support independent rehabilitation training needs to be investigated in the future.

4.4 Stroke Patients' Acceptance of a Smart Garment for Supporting Upper Extremity Rehabilitation

4.4.1 Introduction

Stroke has a high incidence all over the world [3], including China where a recent study found that stroke is the leading cause of adult disabilities in China [3]. In 40 to 50% of stroke survivors, upper extremity function is affected, leading to a decreased quality of life [4, 5]. Stroke impairs the trunk control which is considered important for supporting upper-extremity function[228,229]. The decreased physical mechanisms negatively influence the stability of the shoulder complex and may cause musculoskeletal shoulder pain or dysfunction [226]. According to previous study [9], shoulder pain affects one-third of stroke patients. De Baets et al. [227] explored scapulothoracic control in individuals with stroke as scapulothoracic functioning concerns correct shoulder function.

Often a long rehabilitation process is needed to regain function up to a level that varies from patient to patient, after which point patients are discharged. At that point and given resource limitations such as a limited number of rehabilitation hospitals and limited availability of therapists, it is hard for out-patients to continue their training program at home [188]. For this reason technologies that can support patients continue to train independently are very promising to allow the continuation of training at home. When training at home, technology support may offer motivating feedback that guides towards optimal exercise performance. Training in a home setting is also a solution for cost reduction and improved quality of life outcomes [189]. Training after rehabilitation care in the daily life can improve arm hand function further [190].

Several task oriented training approaches have shown to improve arm hand skilled performance and decrease disability in stroke patients [27, 191]. However, it has been shown that stroke patients show compensatory anterior displacement of the trunk during upper extremity movements such as reaching [12] and grasping [192]. Such compromise the effectiveness of the training, and should be avoided or reduced. Also, De Baets et al. [225] have shown that stroke patients show reduced motor control at the shoulder complex during arm movements. It has also been shown that stabilization of the trunk [193, 194] and shoulder complex [18] leads to improved arm hand performance, and should therefore be taken into account during the rehabilitation program. Wee et al. [195] found external trunk support (wasn't constraining) improved trunk control and upper extremity function in stroke patients. As intrinsic feedback mechanisms are impaired in stroke patients, extrinsic feedback is warranted during the learning process.

There are many wearable technologies being developed to support upper extremity rehabilitation [34]. With wearable and pervasive technologies maturing rapidly in recent years, it has become possible to track posture unobtrusively during daily life, so as to encourage users to correct their posture. The advantages that wearable systems can bring pertain to comfort, ease of use, low cost and accuracy and

Fig.4.9 A subject is instructed of performing task 2 in Huashan hospital.

practical aspects such as not taking space [32]. While it is of major importance to assess the opinion of the system's users, i.e., therapists and patients, regarding their acceptance of technology, the usability and credibility of the proposed technology, and their motivation to use it. In this study, we focus on the stroke patients with limited upper extremity function. In order to find the determining factors of user acceptance and gain insights for further iterations.

4.4.2 Subjects

Inclusion criteria were: 1) diagnosis of stroke, 2) age ≥18, 3) able to give informed consent of participation, 4) able to perform the tasks, 5) ability to read and understand Chinese. Exclusion criteria were: 1) surgery at the shoulder complex or cervical spine in last 6 weeks, 2) presence of aphasia, 3) cognitive disorder, MMSE score ≤17 [10] , 4) Paresis or sensory problems of neurological origin or rheumatoid arthritis or other medically unstable disorders that would intrude the task performance.

4.4.3 Protocol

The ethics board of Huashan Hospital (Shanghai; China) approved the study (No.251 (2014)). The researcher welcomed the participant and gave a brief introduction of the working principle of the garment and explanation of the interface. After giving informed consent, each participant filled in a socio-demographic questionnaire. Participants would put Zishi on and the researcher would provide assistance only when requested. The researcher would adjust the Velcro strip to mount the IMU sensor precisely on the acromion. Afterwards the patient was invited to perform a movement protocol, consisting of 4 standardized tasks: 1) analytical shoulder flexion; 2) placing a cooking pot on a shelf as functional shoulder flexion (as shown in Figure 4.9); 3) analytical elevation in the scapular plane; 4) functional elevation in the scapular plane. (see description in section 4.3.4).

4.4.4 Materials and Outcome Measures

We standardized the materials for the experiments as described in section 4.3.3, Each session took place in the normal training room of the participating hospitals. This study focuses on the evaluation of *Zishi* in terms of patient attitude regarding: intrinsic motivation, technology acceptance, credibility and usability. In this way, we examined the same outcome measurement as explained in section 4.3.4. All the questionnaires were translated from the English version to Chinese and adjusted lexically to fit the context of using *Zishi* while doing the training tasks by our researcher and checked by another Chinese PhD student in rehabilitation department in FuDan University.

4.4.5 Data Analysis

Data from the questionnaires were analyzed with group median scores, interquartile range and one sample Wilcoxon signed-rank test was used to evaluate differences with the neutral point of the scale (SPSS Inc., Chicago, IL). All the subscales in the questionnaire were 7-point Likert rating scales except the CEQ which used a 9-point scale ranging from 1 to 9. We consider the median value of each scale as the neutral score, scores around the neutral score are moderate value, scores higher than neutral are positive, lower than neutral are negative. We applied one-sample Wilcoxon signed rank test to compare the Median score against the scale's neutral score (marked in redline in the Box plot) of each scale.

Table 4.3. Questionnaire Scores List

Factor		Median(IQR)	Sig
Credibility/ Expectancy (CEQ)	Credibility	22.5 (3.5)	0.011
	Expectancy	20.2 (3.55)	0.012
Intrinsic Motivation (IMI)	Interest/Enjoyment	6.43 (0.82)	0.012
	Perceived competence	5.25 (1.96)	0.028
	Effort/Importance	5.8 (1.9)	0.025
	Value /Usefulness	5.93 (1.93)	0.012
	Relatedness	5.6 (2.05)	0.012
	Pressure/Tension	2.2 (2)	0.025
Technology Acceptance (UTAUT)	Performance expectancy	5.37 (1.75)	0.018
	Behavioral Intention	5.67 (1.58)	0.058
	Attitude towards technology	5.3 (0.85)	0.012
	Self-Efficacy	5.25 (1.19)	0.16
	Effort expectancy	5.62 (1)	0.011
	Facilitating conditions	5.25 (1.44)	0.024
Usability (CSUQ)	System usefulness	5.63 (1.53)	0.012
	Interface quality	5.67 (1.33)	0.011

4.4.6 Results from the Patients

17 persons after stroke were recruited from 3 rehabilitation centers: Huashan Hospital, the Tianshan Hospital, and First Rehabilitation Hospital in Shanghai (China). Their mean age was 55 years (*SD* =13.5). However, patients from the First Rehabilitation Hospital were only available to participate in the experiment between their regular training sessions, all tests had to be performed within one day and some patients had to go for examinations and were not available for all tests, therefore their questionnaires are only finished in part. The number of involved subjects for each questionnaire is listed in Table 4.3 together with the results of group Median and one-sample Wilcoxon signed rank test.

Intrinstic Motivation

All 17 subjects filled in the IMI questionnaire (see Figure 4.10). The results on the '*interest/enjoyment*' subscale indicates that the subjects were positively (*MED*=5.14, *IQR*=1.64) motivated to use the system during rehabilitation exercises. The '*perceived competence*' subscale

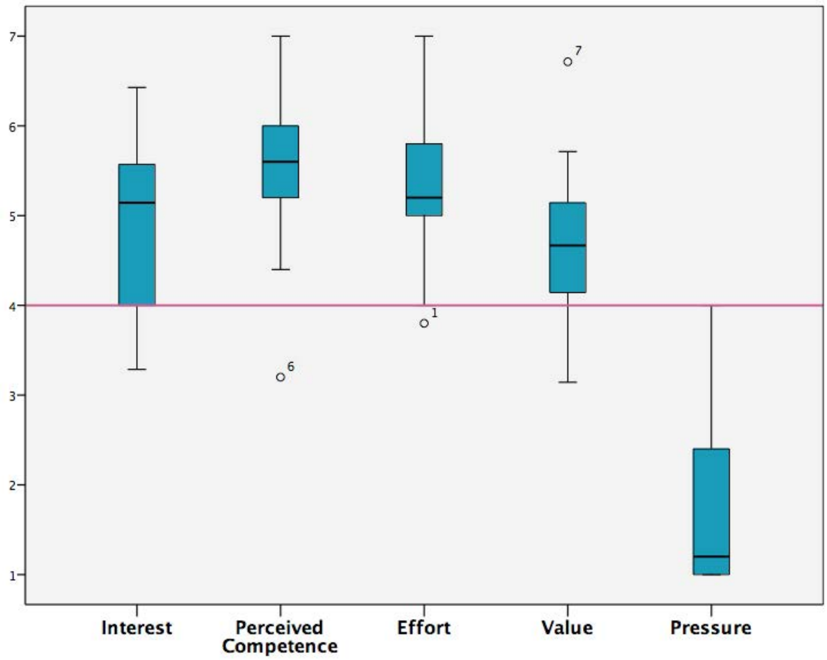


Figure 4.10 Boxplots for the IMI questionnaire subscales.

obtained a high score (*MED* =5.6, *IQR*=1), which suggests that patients considered themselves competent to use the system. The subscale *'value'* was scored moderate (*MDN*=4.67, *IQR*=1.29) which suggests that patients thought training with *Zishi* was moderately important. The subscale 'effort/importance' obtained a good score indicates patients were willing to put effort. The subscale '*pressure'* is scored low and indicates that patients were executing the tasks without pressure.

Technology acceptance and self-efficacy

The UTAUT questionnaire (see Figure 4.11) was filled in by 10 out of the 17 subjects. The subscale '*effort expectancy*' was rated positively (*MED*=5.36, *IQR*=1.94) and indicates that subjects expected little effort

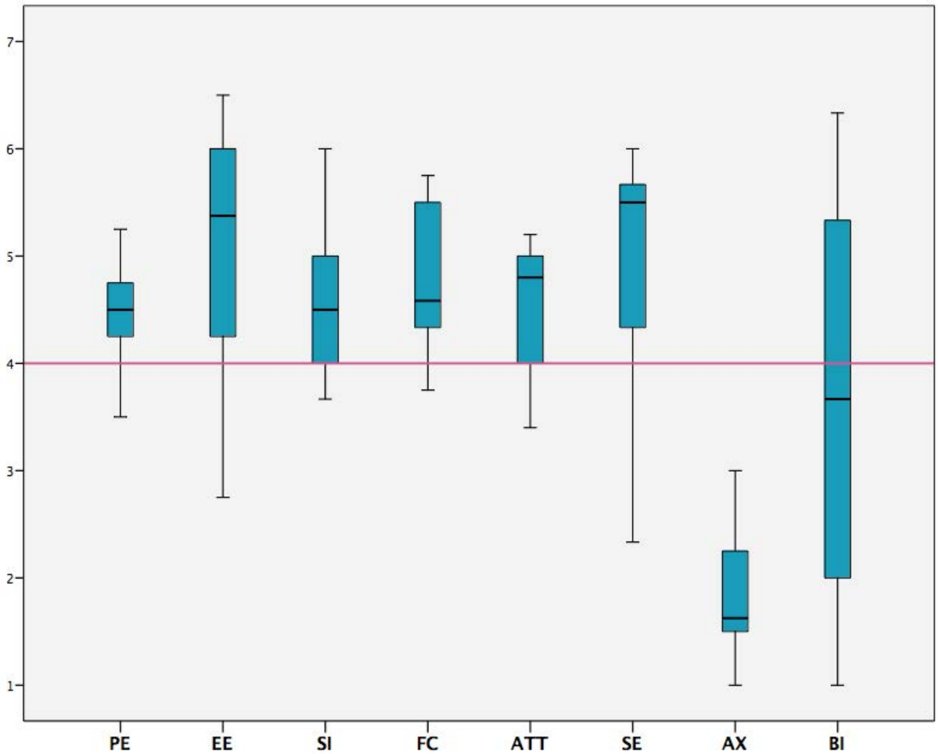


Figure 4.11 Boxplots for the UTAUT questionnaire subscales.

Abbreviations: PE= Performance expectancy, EE=Effort expectancy, SI= Social influence, FC= Facilitating conditions, ATUT=Attitude towards using technology, SE=Self-Efficacy, AX= Anxiety, BI=Behavioral Intention.

to use *Zishi*. Subscale 'performance expectancy' showed that subjects moderately (*MED* =4.5, *IQR*=0.63) believed that *Zishi* would help to improve performance in the training. Also the subscales '*social influence*' resulted in a moderate score, indicating that subjects thought that "*important others*" would probably not use or recommend *Zishi*. *Zishi* does have the potential to be integrated in the current rehabilitation situation and has support on the subscale 'facilitating conditions' as this item was scored slightly higher than the neutral score. Although the abovementioned four factors are strong predictors for behavioral intention (technology acceptance) in the traditional UTAUT model, the subscale 'behavior intention' (*MED* =3.67, *IQR* =3.33) fluctuates a lot in the scale, reflecting a rather high dependence on personal intention. This score was influenced by 3 subjects who gave very low scores(one subject gave score one for each item in 'behavior intention'). However, subjects reported a high 'self-efficacy' score (*MED* =5.5, *IQR*=1.5) and an acceptable score for 'attitude towards technology' (*MED* = 4.8, *IQR*=1.1).

Credibility and Expectancy

Eleven subjects answered the CEQ questionnaire. Patients were neither positive, neither negative about system credibility. The credibility (*MDN* = 16, *IQR* = 4) was slightly higher than the sufficiency threshold (15 over 27), while the expectancy was positive (*MDN*=17.4, *IQR*=4). This indicates that Zishi was considered as a moderately credible system and patients were positive in respect to the expected effectiveness of the system for the improvement of upper extremity performance.

System Usability

Seven subjects completed the CSUQ questionnaire (see Figure 4.12). The system was considered of good usability as the system overall satisfaction score was rated positively (*MED* =5.11, *IQR*=0.95). The information on the screen was also perceived to be really easy to understand as subjects rated it very high for the questions addressing the information presented (*MDN*=5.83, *IQR* = 1.67). System usefulness and interface design was rated above the sufficiency threshold (4 over 7).

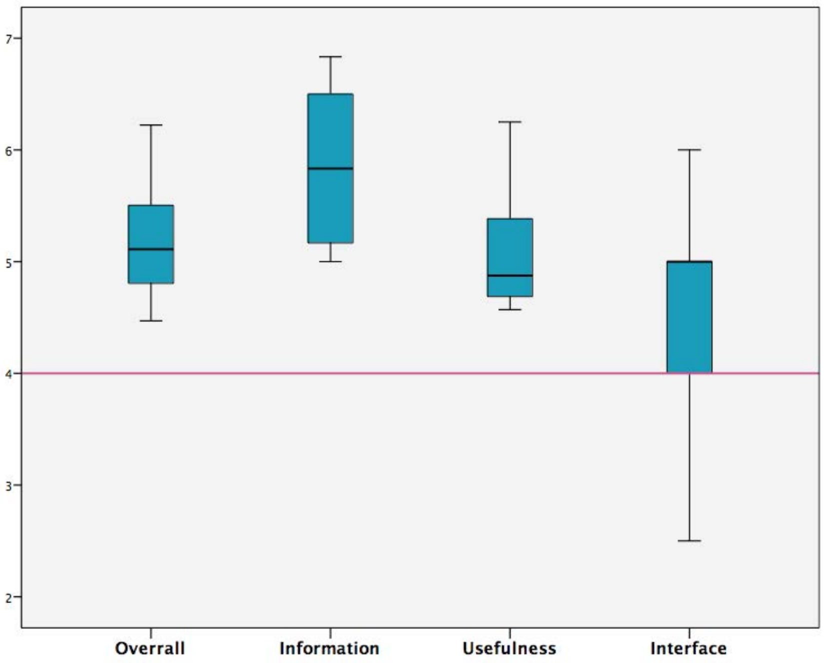


Figure 4.12 Boxplots for the CSUQ questionnaire subscales.

4.4.7 Results from the Therapists

The four therapists who provided instruction for the participating patients answered the 3 questions addressing Credibility in the CEQ questionnaire. Therapists gave a high score with regard to treatment credibility (*MED*=20.5, *IQR* = 6.75), which suggests that they find *Zishi* a credible addition to task training.

Regarding to the open questions, two therapists mentioned that the garment was **easy to put on and take off** (T4). One therapist thought the grey color of the garment is suitable for the hospital while two therapists preferred **multiple color** choices. Three therapists thought the pointer design for feedback was **clear**, while one mentioned the pointer and dashboard on the screen could be even bigger. Two therapists proposed replacing the pointer by animation or by a 3D avatar and one of them suggested VR game integration for enhancing the delectation, this point was confirmed as two of the therapists mentioned the preference of **gamification**. *Zishi* was considered as

convenient and useful: *"It's an intuitive visualization of compensatory movement, convenient and efficient"* (T1), *"Convenient, practically to use and can be widely popularized"* (T2). T3 mentioned that the **audio feedback** was quite helpful for the patients who cannot control their shoulder movement very well. Besides, therapists pointed out their concerns and suggestions: *"Tightness and compactness of the garment need improvement, the interface is a bit plain, more functions such as arm-hand training programs with animation tutorials and remote progress dashboards that could be accessed by therapists are needed for home rehabilitation"* (T1); *"The requirements for the patient's cognitive level is a bit high."* (T2) and *"Not applicable for controlling shoulder movement with patients who are still facing serious obstacles regarding to functional motor ability"* (T3).

4.4.8 Discussion

The purpose of this study has been to evaluate the patients' motivation, technology acceptance, credibility and expectancy and usability with regard to the *Zishi* garment for stroke patients and their therapists. Patients reported high motivation to use *Zishi* and rated its usability favorably, but they expressed moderate confidence in towards using it independently for home rehabilitation.

High Motivation with Smart Garments Supported Training

This study demonstrated high motivation for a wearable system supported training. Stroke patients gave positive scores in terms of 'interest' on the IMI, similarly for the subscale 'attitude towards technology' of UTAUT. These results are compatible with previous findings [27, 80, 127] that patients can be intrinsically motivated towards wearable technology in rehabilitation. Further our results indicated that participants appreciated that the system provides real-time compensation feedback

Usability Analysis

Respondents found both *Zishi* the garment and the application usable, easily to operate by oneself. One major concern for wearability is how easy it is to put the garment on and take it off, which were both appreciated by our participants. *Zishi* fulfilled the requirement that patients are willing to invest little effort for learning a new system. In order to minimize the subject's cognitive load required for information processing, we tried to make the interface simple and only show the essential information. The questionnaire results also reflected this point regarding to the high scores from factors 'perceived competence' from IMI, 'self-efficacy' from UTAUT and 'system information' from CSUQ.

Moderate confidence with Technology in Domestic Environment

The subscales '*value'* from IMI, subscale '*performance expectancy*' from UTAUT, subscale '*credibility*' from CEQ and '*system usefulness'* from CSUQ resulted in mid scores which also explains the mild score of '*Behavioral Intention*'. Based on the feedback from the therapists, this may because of the following context reasons: "*Our patients are not used to do the rehabilitation at home since most of them are inpatients. They are used to train under the supervision of the therapist. Patients relied on therapists in the hospital and were taken good care by their family members or nursing workers at home*" (P3); Further, installation at home may be perceived as a barrier. For example, a recent experimental study requiring participants to use a wearable system for Fugl-Meyer assessment succeeded to recruit 24 patients for using it in a clinical setting, while only 5 participants agreed to join the experiment in a home setting; the reason for this low number was the complexity of the installation and lack of awareness of the importance of home rehabilitation. Besides, two subjects appeared to confuse the research prototypes developed for scientific research with a commercial product, and were worried about being drawn into promotional campaigns, "*I gave score 1 as I thought maybe your agency will call me for product promotion*" (S6). However, therapists gave high score of credibility and good comments of usability for *Zishi*. This indicates that *Zishi* has good potential to be used in the current therapy while to improve the perceptions of usefulness one would need first improve awareness regarding the value of home rehabilitation. Finally, future studies aiming to assess patient attitudes could reduce the role of the researcher in the experiment, letting the whole interaction take place between the therapist and the patient as would be the case for the actual deployment of the technology in therapy.

4.4.9 Future work

Both therapists and patients seemed to need more engaging feedback, asking for example that feedback should be made more playful with the introduction of gaming elements. This also suggest that further developments in feedback should be more adaptable, providing more options for advanced users, such as simple rewards and punishments. More rewarding elements towards their lower compensation movements will be added, for example increasing scores, happy face and encouraging word "well done". In this way, the smart garment system provides feedback on the manner of task performance and will increase a person's confidence in doing the task correctly, improving patients' self-efficacy; While adding such gamification features is straightforward, future research would still need to demonstrate that they enhance the effectiveness of the system in treating stroke.

This study used validated instruments measuring attitudes towards the system that are key to its successful implementation in clinical practice. More extensive studies could try to validate potential relations between these variables in order to understand how different aspects of the system, such as enjoyment, usefulness and usability contribute to the intention to use such wearable posture correction technology. More importantly, behavioural measures regarding adherence to training and the posture during training may be taken to assess the effectiveness of the device, which may be tested extensively in randomized clinical trials.

4.4.10 Conclusion

The results of this study demonstrate that stroke patients are motivated to use Zishi during rehabilitation and they consider the system usable. Patients are hesitant to use the device independently compared to training with therapists. At this moment Zishi is preferred of being used in collaboration with other rehabilitation tasks in a clinical setting. Based on the positive results, we are currently further developing the system, especially taking into account the suggestions about the feedback design for long-term using and potential context of home rehabilitation.

4.5 Discussion

This chapter argues that wearable posture and upper body movement monitoring technology can be of great value for motor control training for rehabilitation. The two usability studies illustrate how technology can monitor compensatory movements for supporting a motor control training program.

Though the patient group's pathology (musculoskeletal shoulder pain vs. stroke) and culture background (Belgium vs. China) were different from one another and participants number was small, the experiment target of improving the training's quality by avoiding compensatory movement was consistent and performed tasks were standardized. We would like to discuss some interesting insights while comparing the results. Results from both studies demonstrated the credibility of the approach, indicated that participants were (intrinsically) motivated to use *Zishi* and *Zishi* was perceived with high usability and wearability, *Zishi* was considered to be a potential aid to support therapists. In the shoulder study, patient attitudes towards the prototype revealed a very positive perception of the system concept. That participants expressed a wish to take *Zishi* home to train was particularly promising. While regarding to the positive reception in terms of technology acceptance in the study conducted in Belgium, participants' attitude towards system usefulness, behavior intention (mainly about will you consider to use *Zishi* at home in future) in the study conducted in China was relatively less. Possible reasons were discussed in section 4.4.6.3 and include limitations of the survey approach used and concerns of Chinese patients towards automation of therapy. Future evaluation studies should consider the use of Zishi in a domestic environment and its adequacy for supporting home rehabilitation training.

5

Zuozi: The design and evaluation of a wearable system supporting shoulder posture correction

This chapter is based on:

1. J Du, Q Wang, L De Baets, P Markopoulos" Supporting shoulder pain prevention and treatment with wearable technology" in Proceedings of the 11th International Conference on Pervasive Computing Technologies for Healthcare, PervasiveHealth '17, Spain,2017;

My contributions to paper 1 is in the planning, the protytpe development (garment), execution of the experiement and writing parts of the paper. The app of Zuozi has been developed by Jiachun Du, as well as the data analysis.

5.1 Introduction

Shoulder pain is very common, adversely influencing arm function and the psychological state of people, decreasing daily life performance and increasing anxiety or depression [196]. A review of 17 studies on the prevalence of shoulder pain found that results range between 6.9–26% for the point prevalence, 18.6–31% for the 1-month prevalence, 4.7–46.7% for 1-year prevalence and 6.7–66.7% for lifelong prevalence [197].

Figure 5.1 Office worker was wearing the posture monitoring garment and using the shoulder training application.

The occurrence of shoulder pain can be related to improper sitting posture and limited exercise for the shoulder joint; it may already afflict people during early adulthood [198]. Poor posture is often associated with computer work as users often maintain poor postures for a long time while focusing on their screens. Researchers have suggested that educating users on how to sit correctly while working with computers can help reduce shoulder pain [199]. However, maintaining a good posture is not simply a matter of knowing how to sit correctly, but of remembering to do so, and being able to comply with related advice consistently.

Advances in wearable sensing open up the possibility to apply technologies for the prevention of musculoskeletal disorders [200]. Wearable technology has been widely used for posture and movement monitoring [201]. Comfort, aesthetics and other practical requirements also need to be addressed along with accuracy and unobtrusiveness in order to enable regular use in different contexts where people live and work. Further, the manner in which postural feedback and advice are presented to users is crucial for the effectiveness and acceptance of such technologies. Currently, most available solutions are limited to simple audio or vibrotactile notifications for poor posture. This help reminds users to correct their posture but can also be annoying or completely ignored if they arrive at an inconvenient moment.

This research explores how wearable technology and multi-model feedback support posture correction and shoulder training exercises in daily computer work (see Figure 5.1). While shoulder pain prevention is interesting for various age groups, this study targets young adults who spend substantial time at a computer while sitting at their desks. The *Zishi* smart garment for posture monitoring [202] has been enhanced to provide vibrotactile notifications at different joint areas in order to suggest adaptations to posture. A supporting application named *ZUOZI* has been designed which supports two modes of operation, a “shoulder trainer” mode and “continuous shoulder tracker” mode.

5.2 Related work

There have been quite a few studies that developed wearable posture monitoring technology. Previous work such as monitoring the posture of the lower back [95, 203] or the trunk [231] have demonstrated the potential wearable systems for tracking posture. Compared to technologies such as optical motion recognition or robot-based tracking, wearable systems can bring advantages pertaining to lower costs, fewer restrictions/constraints upon the operational environment and low intrusiveness, which may even allow their use during daily life. A good example of a low-cost consumer level wearable device is the Lumo lift [204] a device providing vibrotactile feedback for posture correction, reminding its user to stand straight. However, the movement of the shoulder involves several joints that connect to various tendons and muscles and simply keeping the torso straight up does not constitute a correct posture. Rather the shoulder girdle should be stable and relax with arm movements below 60 degrees which is so for most sedentary occupations [205]. Thus to discriminate different postures reliably several sensors needed to be attached to different parts of the body. Wang et al. [154] use IMUs to support posture tracking. They emphasize how attention must be paid to placing sensors accurately and fitting them close to the body to prevent measurement artifacts resulting from deformations or movements of the garment.

Such posture monitoring technologies need to be coupled with effective feedback mechanisms that will help and motivate users to correct their posture. Common to the technologies described above is the emphasis on providing real-time extrinsic feedback regarding the posture, what is often called knowledge of performance [206]. During the initial stages of a posture correction scheme, this may help users to understand how to improve posture, though it could lead to reliance on this feedback [95]. In order to track progress and motivate behavior change, also knowledge of results is required which describes the performance of the subject with respect to a set goal [206]. Typically, a combination of both forms of feedback in order to support motor learning is necessary.

A recent survey of empirical evaluations of posture feedback technologies used in rehabilitation advises against relying exclusively on the visual modality [95]. This is even more so for posture monitoring through the day when the user's visual attention is dedicated to different tasks. Accordingly, researchers have explored the use of haptic feedback intended as a peripheral display [207] and vibrotactile feedback [208]. However, the integration of such feedback with wearable technology capable of monitoring shoulder movements has not been reported yet.

5.3 Overview of ZUOZI

We introduce a shoulder posture tracking and exercise training system which comprises of the smart garment *Zishi* [154] and an android application called *ZUOZI*. The *ZUOZI* application contains two functions: a shoulder trainer and continuous shoulder tracker. These are described briefly below.

5.3.1 Continuous Shoulder Tracker

The continuous shoulder tracker contains two different kinds of feedback: The first is the instant feedback on current posture. If the user is in a correct posture, the ring will be in green with the words

Figure 5.2 Screenshots of continuous shoulder tracker (top) and shoulder trainer (bottom).

"Keep on!" If the user is in a wrong posture, the ring will become red with the words telling "Sit straight!" (see Figure 5.2). If the poor posture lasts for longer than 10 seconds, the application will send a signal for vibration to the vest with Bluetooth. The second is the performance of the user on the hour scale and day scale. Knowledge of results is supported by the summary feedback provided here.

5.3.2 Shoulder Trainer

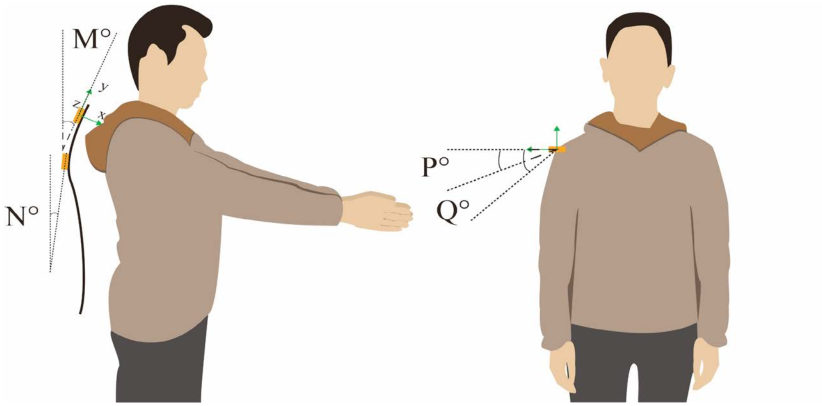


Figure 5.3 The definition of torso and shoulder angle. Two sensors on the spine providing data of angle M and N. Torso angle is the average of them. Sensor on the shoulder provides data of static posture in angle P and moving in angle Q. Shoulder angle is Q minus P.

The self-exercise tutorial instructs users how to perform shoulder training exercises independently. Research already indicates that in persons with musculoskeletal shoulder pain, a scapulothoracic posture retraining program results in reduced shoulder disability and pain [196]. Following the suggestion with the therapists, we included 6 kinds of exercises that required stable scapula, e.g. arm abduction to 40 degrees (see Figure 5.2). The black circle in the middle of the bar is the current value of the 'shoulder angle'. The green part means correct range. The red part means wrong range. Different shoulder exercises have different correct and error range. If the user does a certain shoulder exercise correctly the black circle is expected to fall into the correct range. If the movement is incorrect the black circle will fall into the error range and the system will count an error. The number displayed underneath indicates how many times a shoulder exercise has been done correctly. An animation in the middle shows how to do the exercise with instructions in the text below it.

5.3.3 Detection of Poor Postures

Poor postures are detected by considering both the torso and the shoulder angles (see Figure 5.3). The torso angle refers to the angle between the spine and the vertical plane, and the shoulder angle refers to the shoulder girdle elevation angle. The angle between the torso and the arm does normally not exceed an angle of 45-60 degrees during normal PC work and during which shoulder girdle elevation angle would be lower than 20 degrees. We settled on some thresholds for these values which have to be considered together for the detection of poor postures as explained below.

If the absolute value of the 'shoulder angle' is larger than 20 degrees and smaller than 45 degrees or if the sum of the absolute value of 'shoulder angle' and 'torso angle' is larger than 60 degrees, an error will be recorded because during PC work (arm abduction angle below 45-60°) the shoulder girdle should not elevate much. However, when the angle between the torso and the arm is more than 60° (for example when a user is taking a book from a shelf, taking a cup to drink), then it is naturally accompanied with shoulder girdle elevation more than 45°. As such this should not be counted as an error.

5.4 Iterations of ZUOZI

ZUOZI was implemented on the Samsung Note 3 with the Android operating system. The design went through several iterations following a 'design through research' approach with quick design cycles in search for a suitable feedback strategy. Frequent and informal tests with five volunteers who accepted to try out the system regularly provided formative feedback which guided its iterative design and development. Below we explain more how we shaped the current system based on their feedback.

5.4.1 Iteration Design for Shoulder Trainer Detection of Poor Postures

The first prototype was a series of static pictures that show how to do shoulder exercises (see Figure 5.4). Arrows indicated how the movements need to be corrected. Users proposed several recommendations for improvement during the usability test: *"Could you add animation to the exercises? I can follow it easier."*(P2). *"Is it OK to tell me whether I'm doing the exercises correctly or not by the sensors on the vest?"*(P4). The users valued highly their learning cost, the effort they had to put to learn something new for the application. They asked that the interaction should be consistent with popular designs, for them

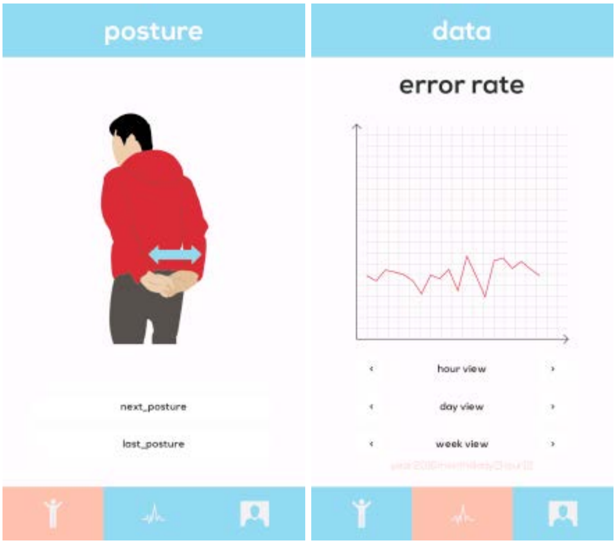


Figure 5.4 Initial design of shoulder trainer and posture tracking.

to understand and use it easily. *"Maybe you should follow the pedometer apps on the market. That would make it easier to understand."* (P5). A lot of design decisions were made with the help of users: (1) Changing the notification colors from blue/red to green/red as in traffic lights; (2) Adding animations for exercises guidance (3) Providing instant feedback from the sensors for the shoulder exercises.

5.4.2 Continuous Shoulder Posture Tracking

As with the shoulder trainer volunteers tried out the application and provided formative feedback. Here we focused on improving the vibration feedback. Earlier work on the understandability of haptic feedback in different contexts has shown that it is difficult to encode complex information using vibration patterns [198, 209] and interpreting vibrotactile notifications requires focal attention by users. Several vibration patterns with different durations (varied from 0.5 seconds to 3 seconds) were evaluated with six users from the target group. Example reactions were: *"I think half a second is not long enough to make me aware if I am working. The longest version (3 seconds) is just good enough because it is comfortable as well as strong enough."* (P2). *"Don't try to vibrate immediately if I did something wrong. Maybe I'm taking my cup! Also to tell me once is enough!"* (P1).

To avoid irritation from multiple alarms, a threshold delay of 10 seconds for error indication was introduced based on a similar study [210]. The duration of the vibration was set to three seconds. This means that if an incorrect posture is detected for longer than 10 seconds, the vibration would be activated once. Thus the system will not give an extra vibration if the user continues to perform incorrect posture. If the user corrects the posture, the vibration alarm will be reset and activated again when it detects incorrect posture next time.

5.5 Evaluation of ZUOZI

The evaluation of *ZUOZI* followed a two-pronged approach. A short-term usability evaluation conducted in context for the shoulder trainer and a one-day field test for the continuous posture tracking. We describe these below.

5.5.1 Evaluation of the Shoulder Trainer

Methods

After the formative evaluations conducted during the iterative development of *ZUOZI*, we set up a summative evaluation of the shoulder trainer (see Figure 5.5). 17 participants, students and staff with ages 18 to 30 (M = 23.06, SD = 2.90, 9 males and 8 females) from our university were invited to a usability test that focused on how able they were to learn to use it for the first time. After being introduced to the system, they were asked to carry out a set of exercises 10 times following the instructions on the interface and they would receive its feedback. They then filled in a standard System Usability Scale [211] questionnaire with rating scales ranging from 1 meaning "strongly disagree" to 5 meaning "strongly agree" and were interviewed briefly regarding their overall experience with the system.

Figure 5.5 A participant going through the usability test.

Results

The SUS scores are shown in figure 5.6. The overall SUS was positive (M = 63.53, SD= 9.23). This compares favourably to the industry-wide mean score of 62.1 of 324 evaluations of products using SUS as reported by [211], which is particularly encouraging considering the early research nature of this prototype. The question "I would imagine that most people would learn to use this system very quickly" was rated the highest (M = 4.35, SD = 0.61) from the questionnaire. The question with the lowest score (M = 1.76, SD = 0.75) is "I need to learn a lot of things before I could get going with this system" which indicates that the efforts made to reduce learning cost were successful.

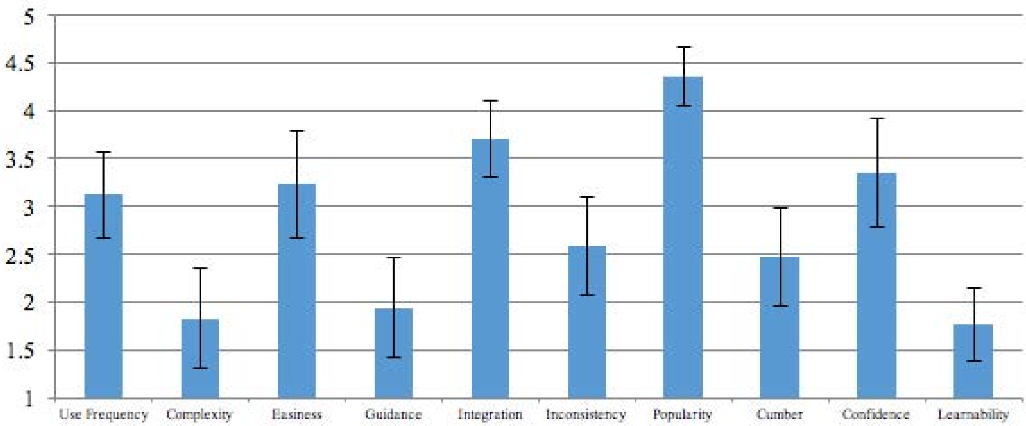


Figure 5.6 Average score of SUS questionnaires. The lines are 95% confidence interval

5.5.2 Field Test of Continuous Posture Tracker

Methods

To evaluate the effectiveness of the system a within-subjects experiment in a field setting was carried out; this was a baseline-treatment-withdrawal design [201, 212]. Here, the treatment concerns the provision of feedback regarding posture. Concretely the first 2 hours would be the baseline stage in which the shoulder posture was tracked, but participants could not receive any feedback from the application (neither visual nor haptic). In the treatment stage which lasted the next 4 hours, participants could check the *ZUOZI* application for feedback on their performance (if they wanted to) and the haptic feedback on the vest was activated. Both haptic and visual feedbacks were removed in the last 2 hours (withdrawal stage) 25 participants, students and staff with ages 18 to 28 (M = 24.08, SD = 3.03, 10 males and 15 females) from our university were invited to the field test. Participants wore the smart vest for 8 working hours (excluding the time of lunch, walking, etc.) to collect posture data. We let them choose wherever they liked to work to disrupt as little as possible their daily routine. They had been informed about the experiment content beforehand, and they received a brief tutorial session of the system before starting the experiment. Then the researcher turned on the system and calibrated it to each participant. The participant was also asked to try a few incorrect postures to feel the change in haptic and visual feedback. After everything was set up properly the actual experiment would start. The start time would be recorded by the researcher. Participants were asked to get on with their work as usual; they could walk around for a rest or go to the toilet or have short discussions as their daily working routine. When they wanted to leave their seat, the vest would be taken off and the data recorded during that time were excluded from the analysis.

To evaluate the overall user experience, we then held a semi-structured interview with each participant which pertained to five main questions: (1) How comfortable is it to wear? (2) How do others react? Do you feel strange to wear it? (3) Describe any interesting events relating to using it. (4) What's your opinion about the feedback? (5) For what reasons might you want to use it for longer?

To gauge the user experience, we used a method called emotional curve based on the Memoline [213]. At the end of the eight-hour trial, participants were asked to draw a curve illustrating how their feelings varied over time during the session: The horizontal axis represented time and the vertical axis the valence of the users' emotions. This way we could capture the evolution of the user experience over time. To do so with other instruments like questionnaires would require repeated measures which can be annoying and interfere with the experience measured itself.

Posture data from *Zishi* was sampled every 5 seconds. Each sample contained year, month, day, hour, minute, second, the "shoulder angle", the “torso angle” and error. Datasets were stored in one XML file in the smartphone. Around 5000 samples were collected during the 8 working hours for each participant. Irrelevant data, such as those collected when the user went out for a phone call, would be excluded in the data analysis. Erroneous data caused by system errors (for example one participant accidentally dropped the battery) was also excluded.

The results are described into two parts: (1) Quantitative data that reveals statistic findings of the posture angles and occurrences of poor posture, (2) Qualitative data that reveals user’s feeling of the experiments and the system.

Quantitative Findings

The measurements of different periods were averaged according to the three different stages. In this section, changes in participants’ posture performance during different stages are reported. Raw data and data after tiredness curve calibration are presented below.

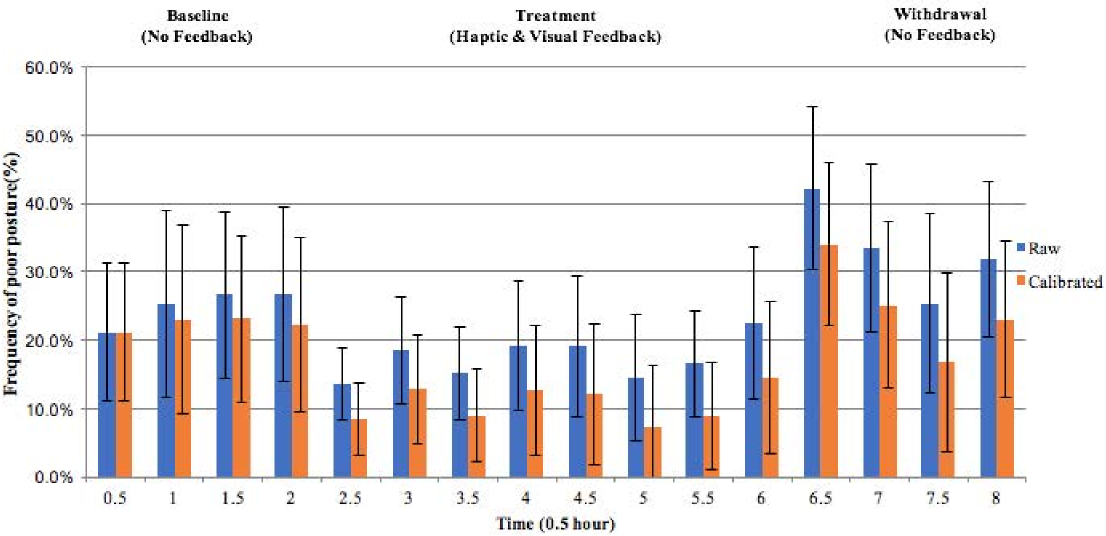


Figure 5.7 Average occurrences of poor posture before and after calibration. From hour 0.5 to 2 is the baseline stage. From hour 2.5 to 6 is the treatment stage. From hour 6.5 to 8 is the withdrawal stage. The X axis is the time unit of half an hour (8 hours in total). The Y axis is the occurrences of poor posture in percentage. The lines are 95% confidence interval.

The raw and calibrated data of occurrences of poor posture is presented in Figure 5.7.

The average occurrences of poor posture of the baseline stage (B) is 24.91% (SD = 27.61%), of the treatment stage (T) is 17.40% (SD = 13.19%), and of the withdrawal stage (W) is 33.24% (SD = 25.73%). A drop was observed in the average of occurrences of poor posture in the treatment stage. The occurrences of poor posture rose higher in the withdrawal stage. However, from the interviews with users, it was found that posture was directly influenced by them getting more tired during the day. For this reason, raw data was transformed by subtracting a tiredness curve representing the temporal variation of posture caused by fatigue.

Table 5.1: Pairwise comparisons of the occurrences of poor posture in different stages for raw data and calibrated data.

	Compare	t-value	p-value
Raw	B vs T	1.483	0.151
	B vs W	-1.239	0.227
	T vs W	-2.907	0.008
Calibrated	B vs T	2.302	0.030
	B vs W	-0.353	0.727
	T vs W	-2.574	0.017

According to [214] the muscle fatigue model should be in the form of natural logarithm A tiredness curve should have a similar form of function $y=\alpha*\ln(x)$, where y is the calibration of occurrences of poor posture and x is the time in the unit of half hour. Parameter α was calculated as the difference between the occurrences of poor posture in the baseline stage minus those in withdrawal stage, divided by ln(16). The function was finally defined as $y = 0.0318*\ln(x)$. After removing the tiredness curve, the average occurrences of poor posture in the baseline stage (B) is 22.38% (*SD* = 27.61%), in the treatment stage (T) is 10.71% (*SD* = 13.19%), and in the withdrawal stage (W) is 24.75% (*SD* = 25.73%).

A repeated measure ANOVA was conducted to compare the effect of the feedback upon the number of poor postures detected in the three different experiment phases (baseline-treatment-withdrawal) (see Table 5.1). A significant effect of providing feedback was found when analyzing both the raw data (F (2,23)=4.494, p=0.023) as well as the calibrated data (F (2,23)=4.834, p=0.018). Pairwise T-tests found a difference between treatment and withdrawal stages for both the raw data (t(24)= -2.907, p=0.008) and the calibrated data after removing the tiredness curve (t(24)=-2.574, p=0.017).

These results provide initial evidence that our system can decrease the occurrence of incorrect sitting posture within a single day. Also, we note a gradual decline in the occurrences of poor posture during the day which may suggest that participants learn to keep a good posture by using the system.

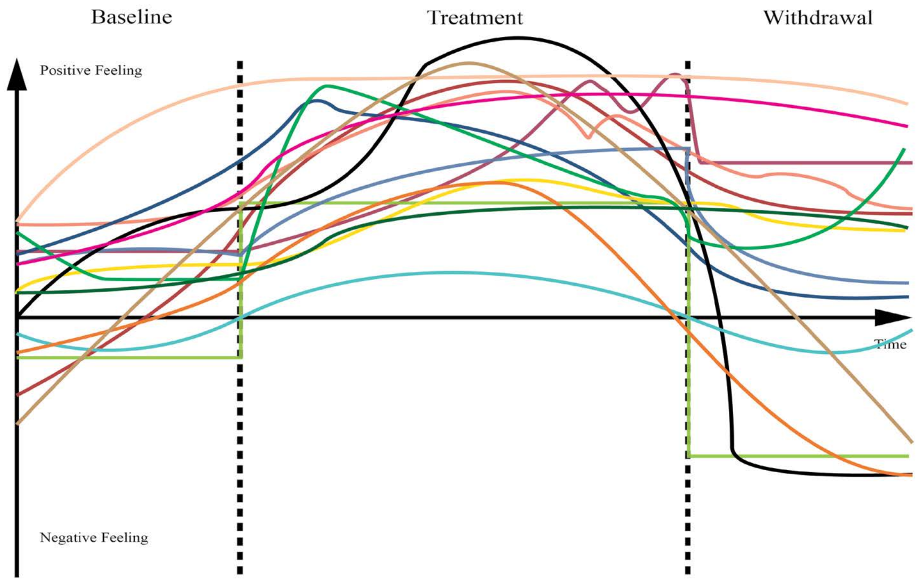
We observe a peak of occurrence of poor postures at the start of the withdrawal stage. This peak exists even if we calculated the trimmed mean. We consider this as a rebound after users suddenly received no feedback from the *ZUOZI* system. We can see in the next 1.5 hour the occurrence of poor postures is recovering to a similar level as the baseline stage. This trend of recovering is more significant if we look at the calibrated data. From this, we can infer that users were relying on the *ZUOZI* system for the feedback of poor postures. After they received no feedback, their sitting habits drew back to the baseline level, which showed the importance of the treatment.

Qualitative Findings

The interviews were recorded, and affinity diagrams were made to classify their quotes thematically. Participants commented on the wearability and the social influence after they used the system for a working day.

Regarding **comfort,** there were few reservations: *"Yes it is comfortable. Except the circuit is on my back and pushes against the back of the seat."* They felt comfortable using the device, e.g., *"Nobody felt strange because the circuit is covered by the cloth."* (P12)

They became quite conscious of it, and in some cases they realized it **influenced their behaviors** in unexpected ways: *"I would intentionally move less because I thought I was wearing a circuit."* (P5)



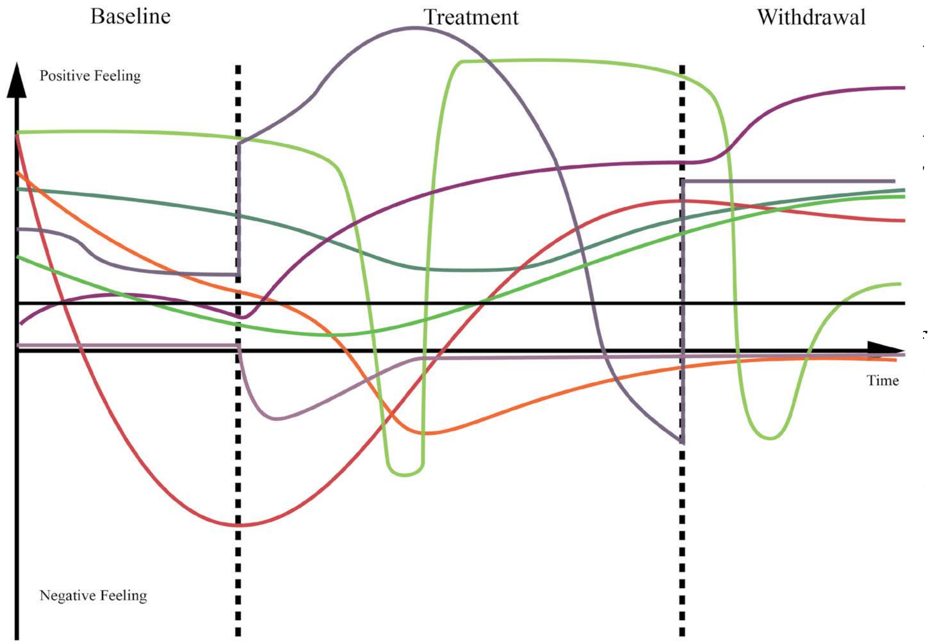


Figure 5.8 Memolines of participants reporting a positive (top) or negative (bottom) feeling compared to other stages in the treatment stage.

groups corresponding to two different patterns that could be found in the reported experiences. The first group describes a positive feeling during the treatment stages with vibration and visual feedback compared to other stages (Figure 5.8, top). In contrast, the second group describes other stages more positive than the treatment stage (Figure 5.8, bottom).

For those who reported positive feelings during the treatment phase, they claimed that the vibration gave them quite a nice feeling. They felt like they were doing something to improve their working postures. Some also benefited from the visual feedback on the smartphone. However, not everyone would check the phone even if they had received vibration feedback.

For those who had a negative feeling in the treatment phase, most of them claimed that the vibration was disturbing. Some felt that the system was difficult to attend to all the time. Also, it appears that feelings related to their work were integrated into the curve.

5.6 Discussion

During the study, most of the users reacted to wearable technology as a novelty. They claimed that they would not use a system that was weird or counterintuitive. Smartphone applications and simple haptic feedback were selected for this study to help them get used to the system with most of its parts being quite familiar.

During the evaluation of the shoulder trainer, it was noted how users mentioned effort or, as they called it, the 'energy' that they spend every day in order to change or maintain desirable behaviors in their daily lives. They would not be prepared to invest much effort into learning and adapting to a new system. For this reason, we prioritized learnability of the system. Several suggestions for improvement were mentioned. Specifically, for the shoulder exercise, it would be good to indicate the user if they are doing correctly or not in real time. Also, animations would work better than simply static pictures.

In the field evaluation of the continuous posture tracker, participants seemed to be very aware of the vest even without any feedback. Wearing the sensors in this way, while new to them, was not something they disliked or resented. Participants held diverse views regarding the intrusiveness of the feedback. One thing they all agreed on was they can easily ignore the feedback when they are in the flow of their work. On the one hand, this is positive as it shows that the system causes little disruption. On the other hand, it could also mean that it may be less effective in real life use: people may be having a poor posture exactly when they are very much absorbed by their work. Longer term field testing in real life use may be needed to examine this issue more thoroughly. Another point worthy of a deeper investigation is applying activity recognition algorithms, so that the system could distinguish sitting from other activities/postures, provide more precise notifications and encouragement during exercises.

Test participants, especially female, complained about the vest for its aesthetics. However, they praised that luckily with the cloth on the circuit few people noticed that they were trying out a prototype. Making the feedback unnoticeable to others is necessary for the acceptance of the system that aimed at behavior change. Aesthetic improvements upon *Zishi* have already been made to address this issue (see Foigure 8 illustrated that the ZISHIigure 5.9), but this improved design was not ready in time for the field tests. Also, contrary to the tested version which is unisex, this new design addresses female users only.

Figure 5.9 Aesthetically redesigned version of the *ZiShi* upper body posture tracking garment.

The field experiment demonstrated that posture is influenced in the expected direction, though further evidence may help consolidate these findings. The data was collected in one day and there is a possibility of reactivity in the results with participants gradually adjusting to the experimenter's expectations. Our results could be strengthened by evaluating behavior on shorter intervals on different days and at different times of the day, to also eliminate the potential confound of tiredness.

5.7 Conclusions and future work

This research examined how wearable technology and supporting applications can help office workers maintain good posture and guide them to carry out shoulder exercises at their workplace. Specifically, we described a smart garment designed to monitor upper body posture that provides vibrotactile notifications at different joint areas in order to remind users to correct their posture. We presented the design and evaluation of a related smartphone application that supports shoulder training exercises to treat and prevent shoulder pain. The usability of the system for shoulder training was evaluated positively in a laboratory test (N=17). The effectiveness of the system for posture monitoring was assessed with a field deployment (N=25) in which students working with laptops used the posture monitoring system for a whole day. The results demonstrate the system can help the participants to improve their posture in sedentary work.

This chapter makes the following contributions: a) it introduces a novel wearable system that can help users carry out shoulder training exercises and continuously monitor their postures b) it presents evidence regarding the usability of the system c) it presents evidence regarding the effectiveness of the system for shoulder posture correction and an evaluation of the user experience during a field trial.

Methodologically this work combines an interesting set of techniques well known and practiced in the field of user experience design, but which have not yet been applied in the domain of personal health informatics and rehabilitation technology. Arguably this chapter can provide a useful example to guide their further fruitful application.

Our evaluation also demonstrated a stepwise approach to evaluating systems aiming to support behavior change. First, the system is designed in an iterative fashion before summative tests are attempted. Then user attitudes and basic usability were evaluated; success in this case was seen as a precondition for moving to a short field test. The field test was just long enough to show the effectiveness towards motivating behavior change and to evaluate how the system is experienced in context. Such evaluations can be either repeated until the effectiveness of the system has been sufficiently demonstrated, or followed up by longer-term field tests to evaluate issues of participant fatigue, dropping out, but also compliance over the longer-term with a behavior change goal.

Our system is representative of an emerging class of technologies that allow more targeted and precise self- tracking than current commoditized general-purpose activity trackers. Like many other aspects of our behavior, movement and life, good posture is hard to maintain, but doing so can provide several benefits to users. Developing interactive technologies that can be worn during long hours, and that can help people achieve changes they wish regarding posture, is an area that will attract more research interest and is likely to be used widely in the next few years.

6 Conclusion

This chapter is based on:

1. R. Bootsman, P. Markopoulos, Q. Qi, Q. Wang, A. Timmermans. " Wearable technology for posture correction at work", (current status: submitted to the International Journal of Human-Computer Studies)

2. J. Du, P. Markopoulos, Q. Wang, M. Toeters, T. Gong. ShapeTex: Implementing Shape-Changing Structures in Fabric for Wearable Actuation. In: Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction. ACM; 2018. p. 166–176.

My contributions to paper 1 is in in its conception and writing parts of the paper. The system development and evaluations have been performed by Rik Bootsman and Qi Qi. My contribution to paper 2 is in the system design and writing parts of the paper. Jiachun developed and evaluated the system.

6.1 Summary of Thesis

Wearable technologies for posture monitoring and posture correction are emerging as a way to support and enhance physical therapy treatment, e.g., for motor control training in neurological disorders or for treating musculoskeletal disorders, such as shoulder, neck, or low back pain. While related research has been primarily concerned with demonstrating the required accuracy and clinical validity of measurements, less attention focused on the requirements of aesthetics, wearability, ease of use and motivation. Therefore, the work presented in this thesis developed a garment for interactive posture correction to be used in rehabilitation and prevention. The central research question of this thesis is: How to design interactive posture correction garments to support rehabilitation?

In Chapter 2, we conducted a systematic review of the study the state-of-art (**RQ1**). We compared published works on interactive wearable systems for movement and posture monitoring during upper body rehabilitation, with respect to the sensing technology they use, system measurements, feedback conditions, system wearability and availability of clinical evidence. The selected 45 articles have been positioned in a cuboid taxonomy with three dimensions: a) Sensing technology, such as Acc/IMU, Flexible angular sensor, E- textile and Others; b) Feedback modalities, namely Visual, Auditory, Haptic and Multi-modal; c) Measurement, as the basis of building a suitable application for specific pathologies includes Range of Motion, Amount of Use and Body Segment Posture. We compared works with respect to sensor placements, classifications from an implementation perspective and with respect to wearability.

In Chapter 3 we set out to find the answers about how to design interactive posture correction garments to support rehabilitation (**RQ2**) and what should be considered when designing interactive posture correction garments to support rehabilitation (**RQ3**)? We have applied the approach of research-through-design by iteratively designing, evaluating the interactive garments and reflecting the generated knowledge. Chapter 3 first presents an interactive posture correction system called *Zishi* (*Zishi* is the pronunciation of a Chinese word "姿势" which means posture, the early iterations named as Smart Rehabilitation Garment), designed to support trunk and scapulothoracic posture training by monitoring compensatory movement and synchronously providing feedback with visual instruction, training overview, auditory feedback on a handheld device and vibration on the garment. Through the six iterations, we have developed a set of smart sensorized garments and modular solutions that support motion tracking by integrating different sensing technologies, smart textiles, motivation strategy and effective multi-modal feedback. Interactive garments as our design prototypes played central role in the generating process of communicated knowledge. The lessons learned through the iterative process, the knowledge gained from multi-disciplines and insights based on the selected papers in Chapter 2 have triggered the formulation of six design lenses: Function, Accuracy, Wearability, Aesthetics, Interactivity and Hard & Soft connection. Subsequently, Chapter 3 illustrates the key considerations of each lens and how we applied the lenses in the design iterations of *Zishi*. Design lenses encapsulate the main considerations in this application area; they can be helpful in this interdisciplinary field as shifting fluently between them may help designers and researchers to focus on a specific perspective while taking into account the diverse design requirements. In the future, we need to explore how the lenses could be employed by other designers or researchers.

Chapter 4 focuses on the evaluation Zishi exploring the extent to which patients and therapists accept the interactive garment for rehabilitation (**RQ4**). The accuracy of posture tracking was assessed by comparing to an optical tracking system (3^{rd} iteration); the accuracy achieved was comparable to the state of the art in wearable systems while arguably improving on aesthetics and wearability substantially. Subsequently, two studies (with the 4^{th} iteration) were conducted to assess users' attitudes towards the system credibility and expectancy, intrinsic motivation, technology acceptance and usability. The study involved eight shoulder pain patients and five therapists. Participants performed 4 tasks (analytical shoulder flexion, functional shoulder flexion placing a cooking pot, analytical flexion in the scapular plane, functional flexion in the scapular plane placing a bottle of water) with guided feedback on a tablet that was provided through inertial sensors embedded in the Zishi system at the scapula and the thoracic spine region. Patients and their therapists found the smart garment system a credible aid for rehabilitation and patients expect it helps towards their recovery. The system was found highly usable and users were motivated to train with the system. Another study focused on stroke patients' acceptance of the interactive garment supported training. We recruited seventeen patients and four therapists from 3 hospitals (in Shanghai, China). Participants performed the four tasks as standardized in the shoulder study. We found that patients were motivated to use Zishi and they consider the system as easy to use. Patients were hesitant to use *Zishi* independently compared to training with therapists.

In Chapter 5, we set out to examine the extent to which the interactive garment can support shoulder posture correction (**RQ5**). Specifically, we examined how *Zishi* and a supporting application called *Zuozi* (Zuozi is the pronunciation of a Chinese word "坐姿" which means sitting posture)can help office workers maintain good posture during a working day and guide them to carry out shoulder exercises at their workplace. In a one-day field test participants used Zishi for continuous posture tracking. Results presented evidence regarding the system's usability and were promising as to its potential to improve shoulder posture correction in real life conditions. The sustainability of such posture correction over the longer term is the subject of future research.

6.2 Contributions

This PhD research resulted in following contributions:

1. **The design and development of *Zishi*.** This thesis presented the design and development of a set of interactive garments for posture correction and potentially supporting motor control training in rehabilitation. To our knowledge, *Zishi* (named as Smart Rehabilitation Garment in earlier studies [215]) was the **first interactive garment system that supports trunk and scapulothoracic motor control training by monitoring compensatory movement and providing tailored real-time feedback**. *Zishi* is different to related wearable systems [34] supporting rehabilitation training, for example, the vest in [10]"page":"1-13","volume":"14","issue":"1","abstract":"Background Evidence indicates that post − stroke rehabilitation improves function, independence and quality of life. A key aspect of rehabilitation is the provision of appropriate information and feedback to the learner. Advances in information and communications technology (ICT acting as containers for holding sensor units and system aimed at broader kinematic data, a full body sensing system for stroke rehabilitation in [145] was not equipped with real-time feedback and results are stored and presented on request, the system presented in [15] focused on reducing trunk compensatory movement based on the Wii remote and the knitted garment in [57] aimed at motivating body movements rather than monitor compensatory movements. *Zishi* illustrates how wearable technology can monitor compensatory movements for supporting motor control training programs for upper-extremity rehabilitation. Besides, the interactive garment system (*Zishi*) improves upon the current state of the art of wearable technologies for rehabilitation as our iterative design process encompassed a broader set of user considerations including aesthetic appearance, wearability, ease of use, motivation.

2. Deeper insights into the attitudes of patients and therapists towards interactive garments for rehabilitation. Before a technical measurement or rehabilitation tool can be clinically applied, it is important to ensure the ease of use of the system [27] and positive attitudes by users towards this technology is required. Through the evaluation studies, the attitudes of patients and therapists towards the system were measured using standardized survey instruments regarding the usability, credibility, acceptance and motivation. The first study focused on musculoskeletal shoulder pain patients (in Hasselt, Belgium) and the second study focused on stroke patients (in Shanghai, China). The two studies demonstrated the credibility of the approach. Further, patients were (intrinsically) motivated to use *Zishi* and *Zishi* was perceived as having high usability and wearability. Zishi can support therapists, since it can be an addition to the manual/verbal/auditory assistance provided to patients.

3. Overview of interactive wearable systems that comprising of feedback for upper body rehabilitation. This thesis presented a systematic review on interactive wearable systems for upper body rehabilitation, regarding the sensing technology, system measurements, feedback conditions, system wearability and availability of clinical evidence. Results indicated that accelerometers and IMUs were most commonly used to monitor and provide feedback to patients on range of motion and movement performance during upper body rehabilitation. Most publications describe systems which are at the stage of feasibility prototypes, reporting evaluations against technical requirements. Some systems have reached the maturity required to support user tests, while clinical evaluations are scarce and further studies are needed to provide evidence on the effectiveness in training and to pave the path towards implementation in clinical settings. We also concluded that future research should focus on integrating advanced textile sensors, improving usability, wearability as well as clinical validation. Our findings and insights could benefit researchers and designers from different backgrounds in biomedical science, engineering, computer science, and rehabilitation sciences in developing and evaluating interactive wearable systems for a specific function in upper body rehabilitation.

4. Design knowledge regarding interactive wearables for rehabilitation. Trough the iterative design process, several insights were gained formulated as six design lenses: Function, Reliability, Wearability, Aesthetics, Interactivity and Hard & Soft connection. Previous studies have already identified design considerations and requirements for wearable systems [62] or sensorized garments [158, 160]. The design lenses extend such views with practical strategies towards designing and developing interactive garment system for rehabilitation; such practical strategies pertain to individual lenses. Designers need to shift between lenses focusing on different perspectives while considering all holistically in a given design context.

5. Preliminary evidence regarding the effectiveness of the interactive garment supporting shoulder posture correction during a field trial. The effectiveness of the system for posture monitoring was assessed with a field deployment (N=25) in which students working with laptops used the posture monitoring system for a whole day. The field study followed a baseline-treatment-withdrawal design, in which a reduction was observed in the average of occurrences of poor posture in the treatment stage based on the quantitative data analysis. Further the evaluation contributes evidence that interactive garment can support posture correction in real life conditions.

6.3 Future work

This thesis presented our research on designing interactive garment for rehabilitation in the past years, while there is extensive space to explore further. We now address three directions for future directions.

6.3.1 Clinical evidence study

This research examined patient attitudes in small-scale studies and with limited exposure to the system. As such, it cannot make claims regarding the effectiveness of the system to support training, for which larger sample sizes and training outcome measures would be needed. Having established the feasibility of the system and its preliminary acceptancy be end-users in a clinical context, a trial on the clinical effectiveness of the system, in comparison to traditional rehabilitation methods, is the next step.

Future studies should examine whether *Zishi* could potentially increase the training time and training efficiency of the training, the future study should also report users' attitudes towards this solution while comparing against similar systems and traditional therapy.

Further, the potential of the system to support independent rehabilitation training needs to be investigated in the future, with efforts on improving the customization of feedback location and modality. Enhance the feedback design to allow for customization of content, modality and scheduling, and summary feedback. Besides, whether the system helps achieve gains the quality and intensity of the rehabilitation needs to be investigated by a field test *Zishi* for training in a home environment.

6.3.2 Smart garment for other pathologies

The evidence presented in this study suggests that Zishi is promising as a technology to support rehabilitation training by helping patients maintain a good posture. This can be useful for several patient groups. So far, the Zishi garment has been evaluated for training with musculoskeletal shoulder pain, stroke patients and shoulder posture correction for sedentary work. Potential future applications include arm-hand training for other patient groups, such as multiple sclerosis patients or spinal cord injury patients, in combination with interactive applications that support exercise programs, as for example The

Zishi garment may be also of great value to monitor compensatory movements in combination with interactive tabletops as in [148], or in combination with tablet applications as in [148] or special purpose training devices such as TagTrainer [19].

We will integrate more functions in interactive garments. For example, concerns wearable sensing technology can be applied for the prevention of occupational low back pain, and more specifically how smart garments can help nurses to maintain correct posture. The BackUp (see Figure 6.1) sensing shirt is fashioned after the nurse uniform and is adorned with sensors to track low back posture. A connected smartphone application provides notifications about adverse low back postures and can provide tips for how to correct posture. Conductive thread was embroidered onto the shirt to create a conductive pattern on which the electronic components could be connected.

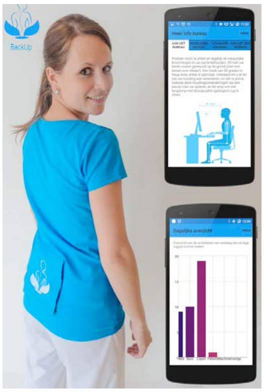


Figure 6.1 BackUp, a smart shirt for tracking lower back posture and the feedback it gives via a smartphone

Notifications of bad posture serve as feedback, promote awareness, but also serve as a form of 'punishment' in applied behavior analysis terms, which encourages them to eliminate the relevant behavior. However, notifying users about adverse posture might not be enough to help them improve it. BackUp is aimed at increasing users' awareness of poor posture, its antecedents and of ways to correct it. Communicating the cause of the poor posture to the user can also increase awareness of which actions can potentially lead to lower back pain. Patients with low back pain have a diminished ability to actively control the movements of the low back due to disturbed intrinsic feedback mechanisms [216]. Therefore it is important to also instruct them how to adjust their posture rather than just giving feedback . The interaction ensures that knowledge about improving one's posture becomes associated to a context/activity. The rationale behind this is that when the shirt is not worn, the environment could still trigger a habit learned while wearing the shirt so that users will correct their posture in a sustainable way.

BackUp has been evaluated in a field test, the evaluation adopted A-B-A-C reversal design using mixed methods to collect both quantitative and qualitative data. Results from the data show that nurses have the motivation and ability to use the system to maintain correct posture. The decrease of occurrences of bad posture in using the system suggest successful outcome of motivational strategy in short term. Further research is now warranted to determine the effectiveness and sustainability of persuasive strategy for behavior change of posture to prevent occupational low back pain in long term.

6.3.3 New forms of wearable actuators

Research in smart textiles and garments has mostly focused on the integration of sensing technology. In order to make garments that are truly interactive it is also essential to develop technologies for actuating smart garments and textiles. The integration of actuators into wearables has been less explored and particularly so with regards to mechanical actuation to support haptic output, movement and shape based output. Traditionally actuation on wearables relies on external mechanism such as motors, shape memory alloy and soft robotics to provide the force for shape transformation.

Figure 6.2 The fabrication of vinyl cutting ShapeTex. (a) design the pattern; (b) use the vinyl cutter to cut the metal sheet; (c) transfer the metal pattern on fabric; (d) remove the excessive part; (e) attach the polymer tape on top.

In order to lower the threshold for prototyping wearable shape-changing interfaces but also to improve the performance of such interactive materials, we need to develop fabrication approaches accessible to designers and to understand the requirements and opportunities designers find in using these new materials. We are developing a novel thermal shape-changing fabric called ShapeTex [217], which has a three layers structure: A thin copper/aluminum layer, a fabric and an ultra-high molecular weight polyethylene (UHMWPE). We explored two fabrication process using etching and vinyl cutting. Figure 6.2 demonstrates the fabrication progress of vinyl cutting which is safer, cleaner, faster and compatibility with aluminum tape in various colors, while etching is more suitable for precise pattern with very thin lines.

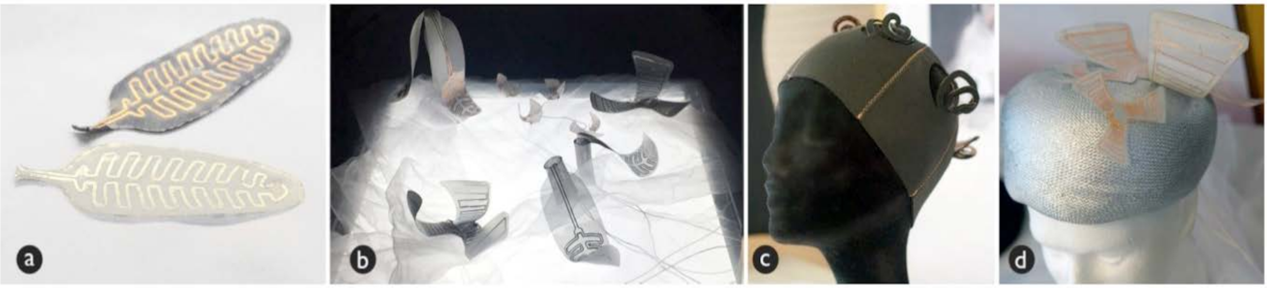


Figure 6.3 (a) ShapeTex samples; (b) Textile Garden is an art exhibit based with several moving pieces simulating leaves and flowers with ShapeTex; (c) Crazy Coil is a fashion design exhibit where coil shaped pieces of ShapeTex that pop up in response to temperature rising in the head; (d) Botanic Hat is a hat-design featuring a ShapeTex flower that blossoms in response to heartbeat variation.

ShapeTex bends when current goes through it and recovers its original shape when it cools down. ShapeTex is accessible to fashion designers and interaction designers. From an aesthetic perspective, designers can display shape-changing information in an aesthetic way with customized metal patterns. Figure 6.3 presents several concept prototypes that help illustrate the relevant space of opportunities. While the limitation is that ShapeTex can only provide small and slow force for visual transformation and cannot suitable of supporting some force feedback (e.g. haptic feedback in rehabilitation training).

Actuation can support new forms of interactivity, providing alternatives to overused modalities such as audio and video with the benefit of a close coupling of feedback to body parts. A major opportunity for research in wearable actuation for rehabilitation pertains to the integration of spatial and temporal aspects of the actuation to sensed human movement. Future work will further explore the integration of ShapeTex in interactive clothing together with fashion, interaction designers and therapy researchers.

Consolidating design knowledge

The proposed design lenses have emerged inductively to summarize and articulate our own design experience but have not yet been applied in a formal study by other designers. In order to ensure their relevance and utility for other designers, they need to be applied prescriptively in a design process and perhaps iteratively improved.

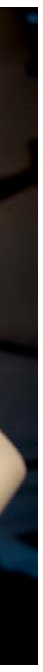
6.4 Concluding Remarks

Wearable sensing technology for posture monitoring and correction has been attracting increasing attention. Since the 1990s when pioneering researchers demonstrated the first smart shirt [218], numerous research projects and products have been developed. Researchers are also attempting to integrate miniaturized computing devices and sensors into textile fabrics for rehabilitation interventions and preventions and now there is the opportunity for the application of smart garments to enhance the quality of life and the experience of their rehabilitation.

To date, there are already various assistant tools and technologies available for posture correction, for example, elastic posture control brace or shoulder tape as passive methods, sensorized cushions, wearable accessory device Lumolift [219], Alex [220] and on-skin device Upright [221] providing notification for bad posture on sedentary work. The commercial success confirmed that these wearable solutions has been well received by early adopters. While we have discussed the advantages of smart garment for rehabilitation with enhanced applicability (multiple body parts monitoring), usability (e.g. easy to operate and unobtrusive), wearability (e.g. comfort as daily clothes), interactivity (e.g. diverse feedback) and aesthetic (e.g. clothing style) in this thesis. Though there are still obvious barriers [222](e.g. manufacturing challenges) to the mass consumer market of smart garments and few adoptions of smart clothing for rehabilitation in current market, the research projects on smart garments for medical and healthcare [223], relevant technologies [38] and social attentions are rapidly growing, not to mention the efforts from high-tech companies like Google [224] (e.g. the Jacquard project, which allow weaving interactive textiles at scale and they have announced smart jacket together with Levi's which integrated Jacquard gesture-sensing threads), we are positive for the near future that smart garment integrate into our life. *Zishi* has been exhibited in the Dutch Design Week in 2015 and in 2017 (see Figure 6.4) ; we used this opportunity to disseminate results to the public and gauge reactions. While this reactions do not by themselves represent reliable research data we noticed a shift in opinion which may be partly due to the development of the garment and partly due to the changing attitudes of the public: the earlier considerations of interactive warables as something distant to their lives have given way to curiosity. Though our research has explored the opportunities and constraints of interactive garment in the context of rehabilitation following a design driven approach rather than a marketing perspective, we anticipate that commercialization and making inroads to the market would accelerate our vision.

Figure 6.4 Zishi was exhibited in exhibitions of 'Manifestations' and 'Do (not) feed the makers' during Dutch Design Week 17'.

Reflecting back the gained knowledge and insights, the next steps for future research are to integrate advanced textile sensors (e.g. soft, flexible and well integrated in textiles or the joining technologies), to explore wearable actuators (e.g. textile display and shape changing interfaces) and to deploy the system in clinical validation (e.g. effectiveness study). Besides, future project need abundant corporations between the researchers from human-computer interaction, rehabilitation, advanced textile technology, biomedical, electronic engineering and industrial design.



Reference

1. Adapted from the work from www.freepik.com, accessed Nov 15, 2017.

2. Langhorne P, Bernhardt J, Kwakkel G. Stroke rehabilitation. The Lancet. 2011;377:1693–702.

3. Béjot Y, Delpont B, Giroud M. Rising stroke incidence in young adults: more epidemiological evidence, more questions to be answered. Am Heart Assoc; 2016.

4. Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, et al. Impact of trunk control on upper extremity function in subacute and chronic stroke patients and healthy controls. Physiotherapy. 2015;101:e1619.

instead the upper one// Wolfe CDA: The impact of stroke. *British Medical Bulletin* 2000, 56:275–286.

5. Nichols-Larsen DS, Clark PC, Zeringue A, Greenspan A, Blanton S. Factors Influencing Stroke Survivors' Quality of Life During Subacute Recovery. 2005;36:1480–4.

6. Körver R, Senden R, Heyligers I, Grimm B. Objective outcome evaluation using inertial sensors in subacromial impingement syndrome: a five-year follow-up study. Physiol Meas. 2014;35:677–86.

7. Ketola S, Lehtinen J, Arnala I, Nissinen M, Westenius H, Sintonen H, et al. Does arthroscopic acromioplasty provide any additional value in the treatment of shoulder impingement syndrome? Bone Jt J. 2009;91-B:1326–34.

8. Luime J, Koes B, Hendriksen I, Burdorf A, Verhagen A, Miedema H, et al. Prevalence and incidence of shoulder pain in the general population; a systematic review. Scand J Rheumatol. 2009;33:73–81.

9. Lindgren I, Jönsson A-C, Norrving B, Lindgren A. Shoulder pain after stroke: a prospective population-based study. Stroke. 2007;38:343–348.

10. Parker J, Mawson S, Mountain G, Nasr N, Zheng H. Stroke patients' utilisation of extrinsic feedback from computer-based technology in the home: a multiple case study realistic evaluation. 2014;14:1–13.

11. Timmermans AA, Seelen HA, Willmann RD, Kingma H. Technology-assisted training of arm-hand skills in stroke: concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. Journal of NeuroEngineering and Rehabilitation. 2009;6:1–18.

12. Cirstea MC, Levin MF. Compensatory strategies for reaching in stroke. Brain. 2000;123:940–953.

13. Levin MF, Kleim JA, Wolf SL. What Do Motor "Recovery" and "Compensation" Mean in Patients Following Stroke? 2008;23:313–9.

14. Lorussi F, Carbonaro N, Rossi D, Paradiso R, Veltink P, Tognetti A. Wearable Textile Platform for Assessing Stroke Patient Treatment in Daily Life Conditions. Frontiers Bioeng Biotechnology. 2016;4:28.

15. Alankus G, Kelleher C. Reducing Compensatory Motions in Motion-Based Video Games for Stroke Rehabilitation. 2014;30:232–62.

16. Thielman G, Kaminski T, Gentile AM. Rehabilitation of Reaching After Stroke: Comparing 2 Training Protocols Utilizing Trunk Restraint. 2008;22:697–705.

17. Thielman G. Rehabilitation of Reaching Poststroke: A Randomized Pilot Investigation of Tactile Versus Auditory Feedback for Trunk Control. 2010;34:138.

18. Worsley P, Warner M, Mottram S, Gadola S, Veeger HEJ, Hermens H, et al. Motor control retraining exercises for shoulder impingement: effects on function, muscle activation, and biomechanics in young adults. Journal of shoulder and elbow surgery. 2013;22:e11–e19.

19. Tetteroo D, Timmermans A, Seelen H, Markopoulos P. TagTrainer: supporting exercise variability and tailoring in technology supported upper limb training. J Neuroeng Rehabil. 2014;11:140.

20. Klaassen B, van Beijnum B-JF, Held JP, Reenalda J, van Meulen FB, Veltink PH, et al. Usability evaluations of a Wearable inertial sensing system and Quality of Movement Metrics for stroke survivors by care Professionals. Frontiers in bioengineering and biotechnology. 2017;5:20.

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

22. www.vicon.com, accessed Sep 20, 2016.

23. Hondori H, Khademi M. A Review on Technical and Clinical Impact of Microsoft Kinect on Physical Therapy and Rehabilitation. 2014;2014:1–16.

24. Burghoorn AW, Dhaeze ER, Faber JS, Wories JWH, Feijs LM, Timmermans AAA. Mirrorcle: Enhanced Visual Feedback to support Motor Learning in Low Back Pain. In: Proceedings of the 3rd 2015 Workshop on ICTs for improving Patients Rehabilitation Research Techniques. ACM; 2015. p. 26–29. http://dl.acm.org/citation.cfm?id=2838951. Accessed 19 Jan 2016.

25. Meng W, Liu Q, Zhou Z, Ai Q, Sheng B, Xie S. Recent development of mechanisms and control strategies for robot-assisted lower limb rehabilitation. Mechatronics. 2015;31:132–45.

26. Duschau-Wicke A, von Zitzewitz J, Caprez A, Lunenburger L, Riener R. Path control: a method for patient-cooperative robot-aided gait rehabilitation. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2010;18:38–48.

27. Timmermans AA, Seelen HA, Geers RP, Saini PK, Winter S, te Vrugt J, et al. Sensor-based arm skill training in chronic stroke patients: results on treatment outcome, patient motivation, and system usability. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2010;18:284–292.

28. Ullah S, Higgins H, Braem B, Latre B, Blondia C, Moerman I, et al. A comprehensive survey of wireless body area networks. Journal of medical systems. 2012;36:1065–1094.

29. Patel S, Park H, Bonato P, Chan L, Rodgers M, others. A review of wearable sensors and systems with application in rehabilitation. J Neuroeng Rehabil. 2012;9:1–17.

30. Bonato P. Advances in wearable technology and applications in physical medicine and rehabilitation. Journal of NeuroEngineering and Rehabilitation. 2005;2:2.

31. Fong DT-P, Chan Y-Y. The use of wearable inertial motion sensors in human lower limb biomechanics studies: A systematic review. Sensors. 2010;10:11556–11565.

32. Hadjidj A, Souil M, Bouabdallah A, Challal Y, Owen H. Wireless sensor networks for rehabilitation applications: Challenges and opportunities. Journal of Network and Computer Applications. 2013;36:1–15.

33. McDaniel TL, Goldberg M, Bala S, Fakhri B, Panchanathan S. Vibrotactile feedback of motor performance errors for enhancing motor learning. In: Proceedings of the 20th ACM international conference on Multimedia. ACM; 2012. p. 419–428.

34. Wang Q, Markopoulos P, Yu B, Chen W, Timmermans A. Interactive wearable systems for upper body rehabilitation: a systematic review. Journal of NeuroEngineering and Rehabilitation. 2017;14:20.

35. Markopoulos P, Timmermans AA, Beursgens L, Van Donselaar R, Seelen HA. 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. IEEE; 2011. p. 5182–5187.

36. Alankus G, Lazar A, May M, Kelleher C. Towards customizable games for stroke rehabilitation. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM; 2010. p. 2113–2122.

37. Klaassen B, van Beijnum B-J, Weusthof M, Hofs D, van Meulen F, Droog E, et al. A full body sensing system for monitoring stroke patients in a home environment. In: International Joint Conference on Biomedical Engineering Systems and Technologies. Springer; 2014. p. 378–393.

38. Fleury A, Sugar M, Chau T. E-textiles in Clinical Rehabilitation: A Scoping Review. Electronics. 2015;4:173–203.

39. Tsekleves E, Paraskevopoulos I, Warland A, Kilbride C. Development and preliminary evaluation of a novel low cost VR-based upper limb stroke rehabilitation platform using Wii technology. 2014;:1–10.

40. Fazio M, Bramanti A, Celesti A, Bramanti P, Villari M. A Hybrid Storage Service for the Management of Big e-Health Data: A Tele-Rehabilitation Case of Study. In: Proceedings of the 12th ACM Symposium on QoS and Security for Wireless and Mobile Networks. ACM; 2016. p. 1–8.

41. Ongvisatepaiboon K, Chan JH, Vanijja V. Smartphone-Based Tele-Rehabilitation System for Frozen Shoulder Using a Machine Learning Approach. In: 2015 IEEE Symposium Series on Computational Intelligence. 2015. p. 811–5.

42.https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/human-computer-interaction-brief-intro, accessed Nov 18, 2017.

43. Ugulino W, Cardador D, Vega K, Velloso E, Milidiú R, Fuks H. Wearable Computing: Accelerometers' Data Classification of Body Postures and Movements. 2012.

44. Bass L, Kasabach C, Martin R, Siewiorek D, Smailagic A, Stivoric J. The Design of a Wearable Computer. In: Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems. New York, NY, USA: ACM; 1997. p. 139–146. doi:10.1145/258549.258634.

45. Lin R, Kreifeldt J. Ergonomics in wearable computer design. Int J Ind Ergonom. 2001;27:259–69.

46. Brendan O, Sanchez J, Angove P, Connolly J, Condell J, Curran K, et al. Novel Smart Sensor Glove for Arthritis Rehabiliation. 2013 Ieee Int Conf Body Sens Networks. 2013;:1–6.

47. Zhang Z-Q, Wu J-K. A Novel Hierarchical Information Fusion Method for Three-Dimensional Upper Limb Motion Estimation. Ieee T Instrum Meas. 2011;60:3709–19.

48. Ricci L, Formica D, Sparaci L, Lasorsa F, Taffoni F, Tamilia E, et al. A New Calibration Methodology for Thorax and Upper Limbs Motion Capture in Children Using Magneto and Inertial Sensors. Sensors. 2014;14:1057–72.

49. Lorussi F, Galatolo S, Rossi D. Textile-Based Electrogoniometers for Wearable Posture and Gesture Capture Systems. Ieee Sens J. 2009;9:1014–24.

50. Birringer J, Danjoux M. Wearable performance. Digit Creat. 2010;20:95–113.

51. Luo Z, Lim CK, Yang W, Tee KY, Li K, Gu C, et al. An interactive therapy system for arm and hand rehabilitation. In: Robotics Automation and Mechatronics (RAM), 2010 IEEE Conference on. IEEE; 2010. p. 9–14.

52. He L, Xu C, Xu D, Brill R. PneuHaptic: delivering haptic cues with a pneumatic armband. In: Proceedings of the 2015 ACM International Symposium on Wearable Computers. ACM; 2015. p. 47–48.

53. Ion A, Wang EJ, Baudisch P. Skin drag displays: Dragging a physical tactor across the user's skin produces a stronger tactile stimulus than vibrotactile. In: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. ACM; 2015. p. 2501–2504.

54. Newbold JW, Bianchi-Berthouze N, Gold NE, Tajadura-Jiménez A, Williams AC. Musically Informed Sonification for Chronic Pain Rehabilitation: Facilitating Progress & Avoiding Over-Doing. In: Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems. New York, NY, USA: ACM; 2016. p. 5698–5703. doi:10.1145/2858036.2858302.

55. https://vimeo.com/129483770, accessed Nov 20, 2017.

56. Yao L, Ou J, Cheng C-Y, Steiner H, Wang W, Wang G, et al. BioLogic: natto cells as nanoactuators for shape changing interfaces. In: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. ACM; 2015. p. 1–10.

57. Bhömer M, Tomico O, Wensveen S. 7 Designing ultra-personalised embodied smart textile services for well-being. 2016.

58. Dunne L. Beyond the second skin: an experimental approach to addressing garment style and fit variables in the design of sensing garments. Int J Fash Des Technology Educ. 2010;3:109–17.

59. Chen M, Ma Y, Song J, Lai C-F, Hu B. Smart Clothing: Connecting Human with Clouds and Big Data for Sustainable Health Monitoring. Mobile Netw Appl. 2016;21:825–45.

60. Chen M, Ma Y, Li Y, Wu D, Zhang Y, Youn C-H. Wearable 2.0: Enabling Human-Cloud Integration in Next Generation Healthcare Systems. Ieee Commun Mag. 2017;55:54–61.

61. Berzowska J. Electronic Textiles: Wearable Computers, Reactive Fashion, and Soft Computation. Text J Cloth Cult. 2005;3:58–75.

62. Seymour S. Fashionable technology: The intersection of design, fashion, science, and technology. Springer Publishing Company, Incorporated; 2008. http://dl.acm.org/citation.cfm?id=1386567.

Accessed 4 Jan 2016.

63. Dunne A, Son D-L, Laighin G, Shen C, Bonato P. Upper Extremity Rehabilitation of Children with Cerebral Palsy using Accelerometer Feedback on a Multitouch Display. 2010 Annu Int Conf Ieee Eng Medicine Biology. 2010;:1751–4.

64. Wang Q, Markopoulos P, Chen W. Smart rehabilitation garment design for arm-hand training. In: Proceedings of the 8th International Conference on Pervasive Computing Technologies for Healthcare. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering); 2014. p. 328–330. http://dl.acm.org/citation.cfm?id=2686965. Accessed 13 Dec 2015.

65. Bhomer M, Tomico O, Hummels C. Vigour: smart textile services to support rehabilitation. In: Proceedings of the Nordic Design Research Conference (NORDES2013). 2013. p. 12.

66. Stoppa M, Chiolerio A. Wearable electronics and smart textiles: a critical review. Sensors. 2014;14:11957–11992.

67. Fellow P, Wulf G. Extrinsic feedback for motor learning after stroke: What is the evidence? Disabil Rehabil. 2009;28:831–40.

68. Subramanian S, Massie C, Malcolm M, Levin M. Does Provision of Extrinsic Feedback Result in Improved Motor Learning in the Upper Limb Poststroke? A Systematic Review of the Evidence. Neurorehab Neural Re. 2010;24:113–24.

69. Pantelopoulos A, Bourbakis N. A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis. Ieee Transactions Syst Man Cybern Part C Appl Rev. 2010;40:1–12.

70. Cancela J, Pastorino M, Tzallas AT, Tsipouras MG, Rigas G, Arredondo MT, et al. Wearability assessment of a wearable system for Parkinson's disease remote monitoring based on a body area network of sensors. Sensors. 2014;14:17235–17255.

71. Zimmerman J, Forlizzi J, Evenson S. Research through design as a method for interaction design research in HCI. In: Proceedings of the SIGCHI conference on Human factors in computing systems. ACM; 2007. p. 493–502.

72. Research through Design. https://www.interaction-design.org/

literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/research-through-design. Accessed 15 Mar 2018.

73. Zimmerman J, Forlizzi J. Research Through Design in HCI. 2014.

74. Mackay WE, Fayard A-L. HCI, natural science and design: a framework for triangulation across disciplines. In: Proceedings of the 2nd conference on Designing interactive systems: processes, practices, methods, and techniques. ACM; 1997. p. 223–234.

75. Wang Q, Chen W, Markopoulos P. Smart Garment Design for Rehabilitation. In: ICTs for Improving Patients Rehabilitation Research Techniques. Springer; 2014. p. 260–269.

76. Wang Q, Chen W, Timmermans AAA, Karachristos C, Martens J-B, Markopoulos P. Smart Rehabilitation Garment for posture monitoring. In: Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE; 2015. p. 5736–5739.

77. Lazar J, Feng JH, Hochheiser H. Research methods in human-computer interaction. Morgan Kaufmann; 2017.

78. Beer A, Treleaven J, Jull G. Can a functional postural exercise improve performance in the cranio-cervical flexion test?–a preliminary study. Manual therapy. 2012;17:219–224.

79. Pfeifer M, Sinaki M, Geusens P, Boonen S, Preisinger E, Minne HW. Musculoskeletal rehabilitation in osteoporosis: a review. Journal of Bone and Mineral Research. 2004;19:1208–1214.

80. Delbressine F, Timmermans A, Beursgens L, De Jong M, van Dam A, Verweij D, et al. Motivating arm-hand use for stroke patients by serious games. In: 34th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. San Diego; 2012.

81. Björklund M, Crenshaw AG, Djupsjöbacka M, Johansson H akan. Position sense acuity is diminished following repetitive low-intensity work to fatigue in a simulated occupational setting. European journal of applied physiology. 2000;81:361–367.

82. Sjölander P, Michaelson P, Jaric S, Djupsjöbacka M. Sensorimotor disturbances in chronic neck pain—range of motion, peak velocity, smoothness of movement, and repositioning acuity. Manual Therapy. 2008;13:122–131.

83. Kortier H, Sluiter V, Roetenberg D, Veltink P. Assessment of hand kinematics using inertial and magnetic sensors. J Neuroeng Rehabil. 2014;11:70.

84. Tormene P, Bartolo M, Nunzio A, Fecchio F, Quaglini S, Tassorelli C, et al. Estimation of human trunk movements by wearable strain sensors and improvement of sensor's placement on intelligent biomedical clothes. Biomed Eng Online. 2012;11:1–8.

85. Uswatte G, Giuliani C, Winstein C, Zeringue A, Hobbs L, Wolf S. Validity of Accelerometry for Monitoring Real-World Arm Activity in Patients With Subacute Stroke: Evidence From the Extremity Constraint-Induced Therapy Evaluation Trial. Arch Phys Med Rehab. 2006;87:1340–5.

86. Bailey R, Klaesner J, Lang C. An Accelerometry-Based Methodology for Assessment of Real-World Bilateral Upper Extremity Activity. Plos One. 2014;9:e103135.

87. Lemmens R, Yvonne J-P, Timmermans A, Smeets R, Seelen H. Recognizing Complex Upper Extremity Activities Using Body Worn Sensors. Plos One. 2015;10:e0118642.

88. Yang C-C, Hsu Y-L. A review of accelerometry-based wearable motion detectors for physical activity monitoring. Sensors. 2010;10:7772–7788.

89. Allet L, Knols RH, Shirato K, Bruin ED de. Wearable systems for monitoring mobility-related activities in chronic disease: a systematic review. Sensors. 2010;10:9026–9052.

90. Wong W, Wong M, Lo K. Clinical Applications of Sensors for Human Posture and Movement Analysis: A Review. 2007;31:62–75.

91. Noorkõiv M, Rodgers H, Price C. Accelerometer measurement of upper extremity movement after stroke: a systematic review of clinical studies. J Neuroeng Rehabil. 2014;11:144.

92. Howcroft J, Kofman J, Lemaire E. Review of fall risk assessment in geriatric populations using inertial sensors. J Neuroeng Rehabil. 2013;10:1–12.

93. Antonio C-V, Alejandro G-M, Williams J. The use of inertial sensors system for human motion analysis. Phys Ther Rev. 2010;15:462–73.

94. Ruth M, Joseph F, Baguley C, Taylor D. A review of e-textiles in neurological rehabilitation: How close are we? J Neuroeng Rehabil. 2016;13:59.

95. Ribeiro D, Sole G, Abbott J, Milosavljevic S. Extrinsic feedback and management of low back pain: A critical review of the literature. Manual Ther. 2011;16:231–9.

96. Saposnik G, Levin M. Virtual Reality in Stroke Rehabilitation A Meta-Analysis and Implications for Clinicians. 2011;42:1380–6.

97. Moher D, Liberati A, Tetzlaff J, Altman DG, Group P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS medicine. 2009;6:e1000097.

98. Wang R, Guo H, Xu J, Ko WH. A supplementary system based on wireless accelerometer network for rehabilitation. In: Nano/Micro Engineered and Molecular Systems (NEMS), 2010 5th IEEE International Conference on. IEEE; 2010. p. 1124–1127.

99. Lee G, Low K, Taher T. Unrestrained Measurement of Arm Motion Based on a Wearable Wireless Sensor Network. Ieee T Instrum Meas. 2010;59:1309–17.

100. Wai AAP, Biswas J, Fook FS, Kenneth LJ, Panda SK, Yap P. Development of holistic physical therapy management system using multimodal sensor network. In: Proceedings of the 3rd International Conference on PErvasive Technologies Related to Assistive Environments. ACM; 2010. p. 26. http://dl.acm.org/citation.cfm?id=1839325. Accessed 28 Jan 2016.

101. Harms H, Amft O, Tröster G. Estimating Posture-Recognition Performance in Sensing Garments Using Geometric Wrinkle Modeling. 2010;14:1436–45.

102. Ambar RB, Poad HBM, Ali AMBM, Ahmad MSB, Jamil MMBA. Multi-sensor arm rehabilitation monitoring device. In: Biomedical Engineering (ICoBE), 2012 International Conference on. IEEE; 2012. p. 424–429. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6179051. Accessed 27 Jan 2016.

103. Fortino G, Gravina R. Rehab-aaService: a cloud-based motor rehabilitation digital assistant. In: Proceedings of the 8th International Conference on Pervasive Computing Technologies for Healthcare.

ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering); 2014. p. 305–308. http://dl.acm.org/citation.cfm?id=2686959. Accessed 29 Jan 2016.

104. Nguyen K, Chen I-M, Luo Z, Yeo S, Duh H. A Wearable Sensing System for Tracking and Monitoring of Functional Arm Movement. Ieee Asme Transactions Mechatronics. 2011;16:213–20.

105. Jeong I cheol, Finkelstein J. Computer-assisted upper extremity training using interactive biking exercise (iBikE) platform. In: Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE. IEEE; 2012. p. 6095–6099.

106. Myllymaa K, Raisamo R, Lylykangas J, Heikkinen J, Surakka V. RehApp – A Wearable Haptic System for Rehabilitation and Sports Training. 2012.

107. Luster EL, McDaniel T, Fakhri B, Davis J, Goldberg M, Bala S, et al. Vibrotactile cueing using wearable computers for overcoming learned non-use in chronic stroke. In: Pervasive Computing Technologies for Healthcare (PervasiveHealth), 2013 7th International Conference on. IEEE; 2013. p. 378–381. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6563971. Accessed 28 Jan 2016.

108. Friedman N, Rowe J, Reinkensmeyer D, Bachman M. The Manumeter: A Wearable Device for Monitoring Daily Use of the Wrist and Fingers. Ieee J Biomed Heal Informatics. 2014;18:1804–12.

109. Holden A, McNaney R, Balaam M, Thompson R, Hammerla N, Ploetz T, et al. CueS: cueing for upper limb rehabilitation in stroke. In: Proceedings of the 2015 British HCI Conference. ACM; 2015. p. 18–25.

110. Lee H-C, Chen K-Y, Hsu S-Y, Wang T-T, Tsai P-W. A Novel Wireless 3D Monitoring System for Physical Rehabilitation. 2015 Ieee Mtt-s 2015 Int Microw Work Ser Rf Wirel Technologies Biomed Healthc Appl Imws-bio. 2015;:49–50.

111. Rahman S, Nusaka S, Shezan F, Sarkar M. The Development of Low Cost Exercise Monitoring Device for Paralytic. 2015 Ieee Int Wie Conf Electr Comput Eng Wiecon-ece. 2015;:530–3.

112. Bittel AJ, Elazzazi A, Bittel DC. Accuracy and Precision of an Accelerometer-Based Smartphone App Designed to Monitor and Record Angular Movement over Time. 2016;22:302–9.

113. Moya S, Grau S, Tost D, Campeny R, Ruiz M. Animation of 3D avatars for rehabilitation of the upper limbs. 2011 Third Int Conf Games Virtual Worlds Serious Appl. 2011;1:168–71.

114. Bleser G, Steffen D, Weber M, Hendeby G, Stricker D, Fradet L, et al. A personalized exercise trainer for the elderly. Journal of ambient intelligence and smart environments. 2013;5:547–562.

115. Ding ZQ, Luo ZQ, Causo A, Chen IM, Yue KX, Yeo SH, et al. Inertia sensor-based guidance system for upperlimb posture correction. Medical Eng Phys. 2013;35:269–76.

116. Spina G, Huang G, Vaes A, Spruit M, Amft O. COPDTrainer: a smartphone-based motion rehabilitation training system with real-time acoustic feedback. In: ACM International Joint Conference on Pervasive and Ubiquitous Computing. 2013. p. 597–606. http://dl.acm.org/authorize?6847880. Accessed 20 Apr 2018.

117. Daponte P, De Vito L, Sementa C. A wireless-based home rehabilitation system for monitoring 3d movements. In: Medical Measurements and Applications Proceedings (MeMeA), 2013 IEEE International Symposium on. IEEE; 2013. p. 282–287. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6549753. Accessed 28 Jan 2016.

118. Ferreira C, Guimarães V, Santos A, Sousa I. Gamification of stroke rehabilitation exercises using a smartphone. In: Proceedings of the 8th International Conference on Pervasive Computing Technologies for Healthcare. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering); 2014. p. 282–285. http://dl.acm.org/citation.cfm?id=2686953. Accessed 28 Jan 2016.

119. Panchanathan R, Rosenthal J, Troy M. Rehabilitation and motor learning through Vibrotactile feedback. 2014;:910717-910717–6.

120. Moreira A, Queirós S, Fonseca J, Rodrigues P, Rodrigues N, Vilaça J. Real-time hand tracking for rehabilitation and character animation. 2014 Ieee 3rd Int Conf Serious Games Appl Heal Segah. 2014;:1–8.

121. O'Flynn B, Torres-Sanchez J, Tedesco S, Downes B, Connolly J, Condell J, et al. Novel Smart Glove Technology as a Biomechanical Monitoring Tool. Sensors & Transducers. 2015;193:23–32.

122. Hermanis A, Cacurs R, Nesenbergs K, Greitans M, Syundyukov

E, Selavo L. Wearable sensor grid architecture for body posture and surface detection and rehabilitation. In: Proceedings of the 14th International Conference on Information Processing in Sensor Networks. ACM; 2015. p. 414–415.

123. Wang Q, Toeters M, Chen W, Timmermans A, Markopoulos P. Zishi: a smart garment for posture monitoring. In: Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems. ACM; 2016. p. 3792–3795.

124. Ploderer B, Fong J, Withana A, Klaic M, Nair S, Crocher V, et al. ArmSleeve: A Patient Monitoring System to Support Occupational Therapists in Stroke Rehabilitation. In: Proceedings of the 2016 ACM Conference on Designing Interactive Systems. Queensland: ACM; 2016. pp. 700–711.

125. Saggio G. A novel array of flex sensors for a goniometric glove. Sensors Actuators Phys. 2014;205:119–25.

126. Halic T, Kockara S, Demirel D, Willey M, Eichelberger K. MoMiReS: Mobile Mixed Reality System for Physical & Occupational Therapies for hand and wrist ailments. 2014 Ieee Innovations Technology Conf. 2014;:1–6.

127. Friedman N, Chan V, Reinkensmeyer A, Beroukhim A, Zambrano G, Bachman M, et al. Retraining and assessing hand movement after stroke using the MusicGlove: comparison with conventional hand therapy and isometric grip training. J Neuroeng Rehabil. 2014;11:76.

128. Salim S, Wan NWZ, Nizhan A, Jamil MMA. Integration of tilt sensors as a device for monitoring rehabilitation process. In: IEEE International Conference on Control System, Computing and Engineering. 2014. p. 232–5. doi:10.1109/ICCSCE.2014.7072721.

129. Rahman YA, Hoque MM, Zinnah KI, Bokhary IM. Helping-Hand: A data glove technology for rehabilitation of monoplegia patients. In: International Forum on Strategic Technology. 2014. p. 199–204. http://ieeexplore.ieee.org/document/6991104/. Accessed 20 Apr 2018.

130. Kapur P, Jensen M, Buxbaum LJ, Jax SA. Spatially distributed tactile feedback for kinesthetic motion guidance. In: Haptics Symposium. 2010. p. 519–26. doi:10.1109/HAPTIC.2010.5444606.

131. Alankus G, Kelleher C. Reducing compensatory motions in

video games for stroke rehabilitation. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM; 2012. p. 2049–2058. http://dl.acm.org/citation.cfm?id=2208354. Accessed 11 Jan 2016.

132. Sigrist R, Rauter G, Riener R, Wolf P. Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. Psychonomic bulletin & review. 2013;20:21–53.

133. Magill RA, Anderson DI. Motor learning and control: Concepts and applications. McGraw-Hill New York; 2007.

134. Gemperle F, Kasabach C, Stivoric J, Bauer M, Martin R. Design for wearability. In: Wearable Computers, 1998. Digest of Papers. Second International Symposium on. IEEE; 1998. p. 116–122. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=729537. Accessed 3 Feb 2016.

135. Gioberto G, Dunne L. Theory and Characterization of a Top-Thread Coverstitched Stretch Sensor. 2012 Ieee Int Conf Syst Man Cybern Smc. 2012;:3275–80.

136. Yamada T, Hayamizu Y, Yamamoto Y, Yomogida Y, Ali I-N, Futaba D, et al. A stretchable carbon nanotube strain sensor for human-motion detection. Nat Nanotechnol. 2011;6:nnano.2011.36.

137. Gong S, Lai DTH, Su B, Si KJ, Ma Z, Yap LW, et al. Highly Stretchy Black Gold E-Skin Nanopatches as Highly Sensitive Wearable Biomedical Sensors. Advanced Electronic Materials. 2015;1:1400063.

138. Steins D, Dawes H, Esser P, Collett J. Wearable accelerometry-based technology capable of assessing functional activities in neurological populations in community settings: a systematic review. Journal of neuroengineering and rehabilitation. 2014;11:1.

139. Ertelt D, Small S, Solodkin A, Dettmers C, McNamara A, Binkofski F, et al. Action observation has a positive impact on rehabilitation of motor deficits after stroke. Neuroimage. 2007;36 Suppl 2:T164-173.

140. Timmermans A, Verbunt J, Woerden R, Moennekens M, Pernot D, Seelen H. Effect of Mental Practice on the Improvement of Function and Daily Activity Performance of the Upper Extremity in Patients With Subacute Stroke: A Randomized Clinical Trial. J Am Med Dir Assoc. 2013;14:204–12.

141. Meyer J, Lukowicz P, Tröster G. Textile pressure sensor for muscle activity and motion detection. In: Wearable Computers, 2006 10th IEEE International Symposium on. IEEE; 2006. p. 69–72.

142. Devendorf L, Lo J, Howell N, Lee JL, Gong N-W, Karagozler ME, et al. "I Don'T Want to Wear a Screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. In: Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems. New York, NY, USA: ACM; 2016. p. 6028–6039. doi:10.1145/2858036.2858192.

143. Perovich L, Mothersill P, Farah JB. Awakened Apparel: Embedded Soft Actuators for Expressive Fashion and Functional Garments. In: Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction. Munich:ACM; 2014. P.77-80.

144. Bader C, Patrick WG, Kolb D, Hays SG, Keating S, Sharma S, et al. Grown, Printed, and Biologically Augmented: An Additively Manufactured Microfluidic Wearable, Functionally Templated for Synthetic Microbes. 3D Printing and Additive Manufacturing. 2016;3:79–89.

145. Klaassen B, van Beijnum B-J, Weusthof M, Hofs D, van Meulen F, Droog E, Luinge H, Slot L, Tognetti A, Lorussi F, Paradiso R, Held J, Luft A, Reenalda J, Nikamp C, Buurke J, Hermens H, Veltink P: A Full Body Sensing System for Monitoring Stroke Patients in a Home Environment. In Biomedical Engineering Systems and Technologies. Volume 511. Cham: Springer International Publishing; 2014:378–393.

146. Lorussi F, Carbonaro N, Rossi D, Tognetti A. A bi-articular model for scapular-humeral rhythm reconstruction through data from wearable sensors. J Neuroeng Rehabil. 2016;13:40.

147. Lin W-Y, Chou W-C, Tsai T-H, Lin C-C, Lee M-Y. Development of a Wearable Instrumented Vest for Posture Monitoring and System Usability Verification Based on the Technology Acceptance Model. Sensors. 2016;16:2172.

148. Beursgens L, Timmermans A, Markopoulos P. Playful arm hand training after stroke. In: CHI'12 Extended Abstracts on Human Factors in Computing Systems. ACM; 2012. p. 2399–2404. http://dl.acm.org/citation.cfm?id=2223809. Accessed 11 Jan 2016.

149. Xavier R-L, Mecheri H, Larue C, Plamondon A. Validation of inertial

measurement units with an optoelectronic system for whole-body motion analysis. Medical Biological Eng Comput. 2017;55:609–19.

150. Schell J. The Art of Game Design: A book of lenses. CRC Press; 2014.

151. Tilde B, Linda de V, Berry E. A toolkit for designing playful interactions: The four lenses of play. Journal of Ambient Intelligence and Smart Environments. 2014;:263–276.

152. Wearing Embodied Emotions - A Practice Based Design Research on | Seçil Uğur | Springer. 2017.

153. Mcgrath MJ, Scanaill CN. Sensor network topologies and design considerations. In: Sensor Technologies. Springer; 2013. p. 79–95.

154. Wang Q, De Baets L, Timmermans A, Chen W, Giacolini L, Matheve T, et al. Motor Control Training for the Shoulder with Smart Garments. Sensors. 2017;17:1687.

155. Brewster SA, Wright PC, Edwards AD. A detailed investigation into the effectiveness of earcons. In: SANTA FE INSTITUTE STUDIES IN THE SCIENCES OF COMPLEXITY-PROCEEDINGS VOLUME-. ADDISON-WESLEY PUBLISHING CO; 1994. p. 471–471.

156. Walter A. Designing for emotion. New York, N.Y: A Book Apart; 2011.

157. Nugroho J. A conceptual framework for designing wearable technology. PhD Thesis. 2013.

158. Andreoni G, Standoli C, Perego P. Defining Requirements and Related Methods for Designing Sensorized Garments. Sensors. 2016;16:769.

159. Tomico O, Wilde D. Soft, embodied, situated & connected: enriching interactions with soft wearables. Mux J Mob User Exp. 2016;5:3.

160. Postolache G, Carvalho H, Catarino A, Postolache O. Smart Clothes for Rehabilitation Context: Technical and Technological Issues. 2017.

161. Deterding S. Skill atoms as design lenses for user-centered gameful design. In: Workshop Papers CHI2013. 2013.

162. https://www.interaction-design.org/literature/article/affinity-diagrams-learn-how-to-cluster-and-bundle-ideas-and-facts, accessed

Dec 5th, 2017.

163. Hochstenbach-Waelen A, Seelen HA. Embracing change: practical and theoretical considerations for successful implementation of technology assisting upper limb training in stroke. Journal of neuroengineering and rehabilitation. 2012;9:52.

164. Wu G, Helm F, Veeger HEJ, Makhsous M, Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. J Biomech. 2005;38:981–92.

165. Cutti A, Giovanardi A, Rocchi L, Davalli A, Sacchetti R. Ambulatory measurement of shoulder and elbow kinematics through inertial and magnetic sensors. 2008;46:169–78.

166. Wearable technologies for personal protective equipment: Embedded textile monitoring sensors, power and data transmission, end-life indicators - Smart Textiles and their Applications - 23. 2017. https://www-sciencedirect-com.dianus.libr.tue.nl/science/article/pii/B9780081005743000230. Accessed 8 Dec 2017.

167.http://www.goose.london/projects/illum/illum-concept/, accessed Oct 16th, 2017.

168. Shimmer imu user guide.

169. Claus A, Hides J, Moseley G, Hodges P. Is 'ideal' sitting posture real?: Measurement of spinal curves in four sitting postures. Manual Ther. 2009;14:404–8.

170. Coyle S, Diamond D. 15 - Medical applications of smart textiles. In: Kirstein T, editor. Multidisciplinary Know-How for Smart-Textiles Developers. Woodhead Publishing; 2013. p. 420–43. doi:10.1533/978 0857093530.3.420.

171. Dunne L, Profita H, Zeagler C: Chapter 1.2. Social Aspects of Wearability and Interaction. Elsevier Inc; 2014:25–44.

172. Griffin L, Compton C, Dunne LE. An Analysis of the Variability of Anatomical Body References Within Ready-to-wear Garment Sizes. In: Proceedings of the 2016 ACM International Symposium on Wearable Computers. New York, NY, USA: ACM; 2016. p. 84–91. doi:10.1145/2971763.2971800.

173.http://xslabs.net/karma-chameleon/site/prototypes.php, accessed Dec 5th, 2017.

174. J M, Morsky S, Dong X. 12 Garment construction: cutting and placing of materials. 2009.

175. Willems L, Tetteroo D, Markopoulos P. Towards Guidelines for the Design of Patient Feedback in Stroke Rehabilitation Technology. In: HEALTHINF. 2015. p. 60–68.

176. Nielsen J. 10 usability heuristics for user interface design. Fremont: Nielsen Norman Group[Consult 20 maio 2014] Disponível na Internet. 1995.

177. Schönauer C, Pintaric T, Kaufmann H. Full Body Interaction for Serious Games in Motor Rehabilitation. In: Proceedings of the 2Nd Augmented Human International Conference. New York, NY, USA: ACM; 2011. p. 4:1–4:8. doi:10.1145/1959826.1959830.

178. Locher I, Sefar AG. Joining technologies for smart textiles. In: Multidisciplinary Know-How for Smart-Textiles Developers. Elsevier; 2013. p. 285–305.

179. http://etextile-summercamp.org, accessed Dec 5th, 2017.

180. http://www.kobakant.at/DIY/, accessed Dec 5th, 2017.

181. Bland JM, Altman DG. Measuring agreement in method comparison studies. Stat Methods Med Res. 1999;8:135–60.

182. Understanding Bland Altman analysis. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4470095/. Accessed 22 Mar 2018.

183. Mottram SL. Dynamic stability of the scapula. Manual therapy. 1997;2:123–131.

184. Devilly G, Borkovec T. Psychometric properties of the credibility/expectancy questionnaire. J Behav Ther Exp Psy. 2000;31:73–86.

185. Monteiro V, Mata L, Peixoto F. Intrinsic Motivation Inventory: Psychometric Properties in the Context of First Language and Mathematics Learning. Psicologia Reflexão E Crítica. 2015;28:434–43.

186. Venkatesh V, Morris MG, Davis GB, Davis FD. User acceptance of information technology: Toward a unified view. MIS quarterly. 2003;:425–478.

187. Lewis J. IBM computer usability satisfaction questionnaires: Psychometric evaluation and instructions for use. Int J Hum-comput Int. 1995;7:57–78.

188. Xiao Y, Zhao K, Ma Z-X, Li X, Qiu Y-P. Integrated medical rehabilitation delivery in China. Chronic Dis Transl Medicine. 2017;3:75–81.

189. Noel HC, Vogel DC, Erdos JJ, Cornwall D, Levin F. Home telehealth reduces healthcare costs. Telemedicine Journal & e-Health. 2004;10:170–183.

190. Timmermans A, Seelen H, Willmann R, Bakx W, Ruyter B, Lanfermann G, et al. Arm and hand skills: Training preferences after stroke. Disabil Rehabil. 2009;31:1344–52.

191. Van der Lee JH, Wagenaar RC, Lankhorst GJ, Vogelaar TW, Devillé WL, Bouter LM. Forced use of the upper extremity in chronic stroke patients: results from a single-blind randomized clinical trial. Stroke. 1999;30:2369–2375.

192. Michaelsen SM, Jacobs S, Roby-Brami A, Levin MF. Compensation for distal impairments of grasping in adults with hemiparesis. Experimental Brain Research. 2004;157:162–173.

193. Michaelsen S, Dannenbaum R, Levin M. Task-Specific Training With Trunk Restraint on Arm Recovery in Stroke Randomized Control Trial. Stroke. 2006;37:186–92.

194. A R-B, Feydy A, Combeaud M, Biryukova E, Bussel B, Levin M. Motor compensation and recovery for reaching in stroke patients. Acta Neurol Scand. 2003;107:369–81.

195. Wee. Effect of Trunk Support on Upper Extremity Function in People With Chronic Stroke and People Who Are Healthy. 0.

196. Badcock LJ, Lewis M, Hay EM, McCarney R, Croft PR. Chronic shoulder pain in the community: a syndrome of disability or distress? Annals of the rheumatic diseases. 2002;61:128–131.

197. Bosman S, Groenendaal B, Findlater JW, Visser T, Graaf M de, Markopoulos P. GentleGuide: An Exploration of Haptic Output for Indoors Pedestrian Guidance. In: Human-Computer Interaction with Mobile Devices and Services. Springer, Berlin, Heidelberg; 2003. p. 358–62. doi:10.1007/978-3-540-45233-1_28.

198. Carignan C, Liszka M. Design of an arm exoskeleton with scapula motion for shoulder rehabilitation. In: Advanced Robotics, 2005. ICAR'05. Proceedings., 12th International Conference on. IEEE; 2005. p. 524–531.

199. Benini MJS, Bruinink M, Pekel AD, Talbott WA, Visser A, Markopoulos P. Restoring balance: replacing the vestibular sense with wearable vibrotactile feedback. In: Smart Healthcare Applications and Services: Developments and Practices. IGI Global; 2011. p. 283–301.

200. Carr EG, Newsom CD, Binkoff JA. Escape as a factor in the aggressive behavior of two retarded children. Journal of Applied Behavior Analysis. 1980;13:101–117.

201. Dunne LE, Walsh P, Hermann S, Smyth B, Caulfield B. Wearable monitoring of seated spinal posture. IEEE transactions on biomedical circuits and systems. 2008;2:97–105.

202. Finley M, Lee R. Effect of sitting posture on 3-dimensional scapular kinematics measured by skin-mounted electromagnetic tracking sensors. Arch Phys Med Rehab. 2003;84:563–8.

203. Ribeiro DC, Sole G, Abbott JH, Milosavljevic S. The effectiveness of a lumbopelvic monitor and feedback device to change postural behavior: a feasibility randomized controlled trial. journal of orthopaedic & sports physical therapy. 2014;44:702–711.

204. Lumo Lift Posture Coach & Lumo Run Smart Running Shorts. (n.d.). Retrieved September 8, 2016, from http://www.lumobodytech.com/.

205. Fraser J. Managing the risks of sedentary working. Occupational Health & Wellbeing. 2017;69:27.

206. Schmidt RA, Wrisberg CA. Motor learning and performance: A situation-based learning approach. Human Kinetics; 2008.

207. Van Almkerk M, Bierling BL, Leermakers N, Vinken J, Timmermans AA. Improving posture and sitting behavior through tactile and visual feedback in a sedentary environment. In: Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE. IEEE; 2015. p. 4570–4573.

208. Rajanna V, Vo P, Barth J, Mjelde M, Grey T, Oduola C, et al.

KinoHaptics: An Automated, Wearable, Haptic Assisted, Physio-therapeutic System for Post-surgery Rehabilitation and Self-care. J Med Syst. 2016;40.

209. Bongers PM. The cost of shoulder pain at work: variation in work tasks and good job opportunities are essential for prevention. British Medical Journal Publishing Group; 2001.

210. Lin C-Y, Tsai C-M, Shih P-C, Wu H-C. Development of a novel haptic glove for improving finger dexterity in poststroke rehabilitation. Technology and Health Care. 2016;24:S97–S103.

211. Lewis JR, Sauro J. The factor structure of the system usability scale. In: International conference on human centered design. Springer; 2009. p. 94–103.

212. Miltenberger RG. Behavior modification: Principles and procedures. Cengage Learning; 2011.

213. Vissers J, De Bot L, Zaman B. MemoLine: evaluating long-term UX with children. In: Proceedings of the 12th International Conference on Interaction Design and Children. ACM; 2013. p. 285–288.

214. Ma L, Chablat D, Bennis F, Zhang W, Guillaume F: A new muscle fatigue and recovery model and its ergonomics application in human simulation. Virtual and Physical Prototyping, 2010, 5(3), 123–137.

215. Wang Q. Designing Posture Monitoring Garments to Support Rehabilitation. In: Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction. ACM; 2016. p. 709–712.

216. Brumagne S, Cordo P, Verschueren S. Proprioceptive weighting changes in persons with low back pain and elderly persons during upright standing. Neurosci Lett. 2004;366:63–6.

217. Du J, Markopoulos P, Wang Q, Toeters M, Gong T. ShapeTex: Implementing Shape-Changing Structures in Fabric for Wearable Actuation. In: Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction. ACM; 2018. p. 166–176.

218. Park S, Jayaraman S. Enhancing the Quality of Life Through Wearable Technology. Ieee Eng Med Biol. 2017;22:41–8.

219. Lumolift. https://www.lumobodytech.com/lumo-lift/. Accessed Dec 13, 2017.

220. Alex. https://alexposture.com. Accessed Dec 13, 2017.

221. Upright. https://www.uprightpose.com. Accessed Dec 13, 2017.

222. Dunne L. Smart Clothing in Practice: Key Design Barriers to Commercialization. Fash Pract J Des Creative Process Fash Industr. 2010;2:41–66.

223. Koncar V. 1 Introduction to smart textiles and their applications. 2016.

224. Poupyrev I, Gong N-W, Fukuhara S, Karagozler ME, Schwesig C, Robinson KE. Project Jacquard: interactive digital textiles at scale. In: Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems. ACM; 2016. p. 4216–4227.

225. De Baets L, Jaspers E, Janssens L and Van Deun S: Characteristics of Neuromuscular Control of the Scapula after Stroke: A First Exploration. Frontiers in Human Neuroscience,2014, 8:767.

226. Ryeson, S., & Levit, K. (1997). The shoulder in hemiplegia. In R. Donatelli (Ed.), Physical therapy of the shoulder (third edition, pp. 205–227). New York: Chirchill Livingstone Inc.

227. De Baets L, Deun S, Monari D, Jaspers E. Three-dimensional kinematics of the scapula and trunk, and associated scapular muscle timing in individuals with stroke. Hum Mov Sci. 2016;48:82–90.

228. Verheyden G, Nieuwboer A, Mertin J, et al. . The Trunk Impairment Scale: a new tool to measure motor impairment of the trunk after stroke. Clin Rehabil . 2004;18:326–334.

229. Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, et al. Impact of trunk control on upper extremity function in subacute and chronic stroke patients and healthy controls. Physiotherapy. 2015;101:e1619.

230. Uman LS. Systematic Reviews and Meta-Analyses. Journal of the Canadian Academy of Child and Adolescent Psychiatry. 2011;20(1):57-59.

231 Wong, W. Y., & Wong, M. S. (2008). Trunk posture monitoring with inertial sensors. European Spine Journal, 17(5), 743–753.

Appendix

This appendix presents the English version of all the questionnaires. Origianl questionnaires used in the study of motor control training for the shoulder with smart garments were in Dutch. Origianl questionnaires used in the study of stroke patients' acceptance of a Smart garment for supporting upper extremity rehabilitation were in Chinese.

Credibility and Expectancy Questionnaire

We would like you to indicate below how much you believe, right now, that the therapy you are receiving will help to improve your lifestyle / functioning. Belief usually has two aspects to it: (1) what one thinks will happen and (2) what one feels will happen. Sometimes these are similar; sometimes they are different. Please answer the questions below. In the first set, answer in terms of what you think. In the second set answer in terms of what you really and truly feel. We do not want your course convenors to ever see these ratings, so please keep the sheet covered when you are done.

Set I

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

1. At this point, how logical does the course offered to you seem?

1	2	3	4	5	6	7	8	9
not at all logical				somewhat logical				very logical

2. At this point, how successfully do you think this system will be for the treatment of your shoulder symptoms?

1	2	3	4	5	6	7	8	9
not at all logical				somewhat logical				very logical

3. How confident would you be in recommending this course to a friend who experiences similar problems?

1	2	3	4	5	6	7	8	9
not at all logical				somewhat logical				very logical

4. How much improvement do you think will have occurred in your shoulder symptoms at the end of the therapy?

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
not at all logical					somewhat logical					very logical

Set II

For this set, close your eyes for a few moments, and try to identify what you really feel about the system and its likely success. Then answer the following questions.

1. How much do you really **feel** that the therapy will help you reduce your shoulder symptoms?

1	2	3	4	5	6	7	8	9
not at all logical				somewhat logical				very logical

2. How much improvement do you **feel** that symptoms will have occurred at the end of the therapy in your shoulder?

not at all logical	somewhat logical	very logical

Intrinsic Motivation Inventory

B For each of the following statements, please indicate how true it is for you, using the following scale:

1 2 3 4 5 6 7

not at all true somewhat true very true

Interest/Enjoyment

1. I really enjoyed this training.

1 2 3 4 5 6 7

not at all true somewhat true very true

2. This training was fun to do.

1 2 3 4 5 6 7

not at all true somewhat true very true

3. I found this was a boring training.

1 2 3 4 5 6 7

not at all true somewhat true very true

4. This training did not hold my attention at all.

1 2 3 4 5 6 7

not at all true somewhat true very true

5. I would describe this training as very interesting.

1 2 3 4 5 6 7

not at all true somewhat true very true

6. I thought this training was quite enjoyable.

1 2 3 4 5 6 7

not at all true somewhat true very true

7. While I was doing this activity, I was thinking about how much I enjoyed it.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

Perceived Competence

8. I think I am pretty good at this training.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

9. I think I do this training pretty well compared to other participants.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

10. After working at this training for a while, I felt pretty competent.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

11. I am satisfied with my performance at this training.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

12. I was pretty skilled at performing this training activity.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

13. This was an activity that I couldn’t do very well.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

Effort/Importance

14. I have put a lot of effort into this training.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

15. I didn't try very hard to do well at this training.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

16. I tried very hard on this training.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

17. It was important to me to do well at this task.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

18. I have not put much energy into the training activity.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

Pressure/Tension

19. I did not feel nervous at all while doing this.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

20. I felt very tense while doing this training.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

21. I was very relaxed while doing these exercises.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

22. I was anxious while working on this training.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

23. I felt that I was under pressure during training.

1 2 3 4 5 6 7

not at all true somewhat true very true

Value/Usefulness

24. I believe this training could be of some value to me.

1 2 3 4 5 6 7

not at all true somewhat true very true

25. I think this activity is useful for improving my shoulder symptoms.

1 2 3 4 5 6 7

not at all true somewhat true very true

26. I think this training is important because I can use my shoulder and arm-hand more and better.

1 2 3 4 5 6 7

not at all true somewhat true very true

27. I would be willing to do this again because it has some value to me.

1 2 3 4 5 6 7

not at all true somewhat true very true

28. I think that doing this activity could help me to use my affected arm and hand more in everyday activities.

1 2 3 4 5 6 7

not at all true somewhat true very true

29. I believe doing this activity could be beneficial to me.

1 2 3 4 5 6 7

not at all true somewhat true very true

30. I think this is an important activity.

1 2 3 4 5 6 7

not at all true somewhat true very true

Relatedness

31. I felt really distant to this training.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

32. I would like to get a chance to practice this training method/ training system more often.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

33. I would like to practice this training method / training system more often.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

34. I do not feel that I can really trust this training method / system.

1	2	3	4	5	6	7
not at all true			somewhat true			very true

35. I am attracted to this training method / training system

1	2	3	4	5	6	7
not at all true			somewhat true			very true

The Unified Theory of Technology Acceptance Questionnaire (UTAUT)

For each statement, indicate the extent to which you agree with it. Use the following scale:

1	2	3	4	5	6	7
totally disagree						totally agree

I think the vest and the feedback are useful for my rehabilitation.	1 2 3 4 5 6 7
Working with the vest and the feedback is fun.	1 2 3 4 5 6 7
The vest and the feedback intimidate me.	1 2 3 4 5 6 7
By using the vest and the feedback, I can perform some tasks faster.	1 2 3 4 5 6 7
I could work with the system if I had a built-in help function for assistance.	1 2 3 4 5 6 7
People who are important to me think that I should use the system.	1 2 3 4 5 6 7
In general, the organization has support the use of the system.	1 2 3 4 5 6 7
I feel apprehensive about using the system.	1 2 3 4 5 6 7
If I could take the system home, I predict I would use the system in the coming months.	1 2 3 4 5 6 7
I think my interaction with the system would be clear and understandable.	1 2 3 4 5 6 7
I could work with the system if I had a lot of time for the task for which the system was designed.	1 2 3 4 5 6 7
I have the necessary resources for the vest and feedback system.	1 2 3 4 5 6 7
I find the vest and the feedback easy to use.	1 2 3 4 5 6 7
I'm afraid I may lose a lot of information by pressing a wrong button when using the feedback system.	1 2 3 4 5 6 7
I could work with the system if no one around to give me instructions.	1 2 3 4 5 6 7
If I could take the system home, I would expect to use the system in the coming months.	1 2 3 4 5 6 7
Using the vest and the feedback is a good idea.	1 2 3 4 5 6 7
I would find the system useful.	1 2 3 4 5 6 7
A specific person is available for assistance with problems with the vest and feedback system.	1 2 3 4 5 6 7

The management of the organization helped me with the use of the vest and feedback.	1 2 3 4 5 6 7
Using the vest and the feedback is a bad idea	1 2 3 4 5 6 7
By using the vest and the feedback, my productivity increases.	1 2 3 4 5 6 7
If I could get the system home, I would plan to use the system in the coming months.	1 2 3 4 5 6 7
I could work with the system if I can ask someone for help when I get stuck.	1 2 3 4 5 6 7
The vest and the feedback makes my training more interesting.	1 2 3 4 5 6 7
People who have influence on my behavior think that I should use the vest and the feedback.	1 2 3 4 5 6 7
I think I can easily become skillful at using of the vest and feedback system.	1 2 3 4 5 6 7
I hesitate to use the vest and the feedback, because I am afraid to make mistakes that I can not repair.	1 2 3 4 5 6 7
It is easy for me to learn how to use the Vest and the feedback.	1 2 3 4 5 6 7
I have the knowledge necessary to use the vest and feedback system.	1 2 3 4 5 6 7
I can not use the vest and the feedback in combination with other systems I use.	1 2 3 4 5 6 7
I like to work with the vest and feedback system	1 2 3 4 5 6 7

To remind you of the scale:

1 2 3 4 5 6 7

totally disagree totally agree

The Computer System Usability Questionnaire

1. In general, I am satisfied how easy this system is to use.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
2. It was easy to do this system.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
3. I can effectively complete my training using this system.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
4. I am able to complete my training quickly using this system.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
5. I am able to efficiently complete my training using this system.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
6. I feel comfortable using this system	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
7. It was easy to learn to use the system.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
8. I believe I become productive quickly using the system.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
9. The system gives error messages that clearly tell me how to fix problems.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
10. Whenever I make a mistake using the system, I recover easily and quickly.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
11. The information(such as on-line help, on-screen messages and other documentation) provided with this system is clear.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
12. It is easy to find the information I need.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
13. The information provide with the system is easy to understand.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
14. The information is effective in helping me complete my work.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
15. The organization of information on the system screens is clear.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
16. The interface of the system is pleasant.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	

17. I like using the interface of this system.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
18. This system has all the functions and capabilities I expect it to have.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	
19. Overall, I am satisfied with this system.	Strongly disagree	1 2 3 4 5 6 7	Strongly agree	

Publications

Publications related to this thesis

Journal Paper:

Q. Wang, L. De Baets, A. Timmermans, W. Chen, L. Giacolini, T. Matheve and P. Markopoulos, “Motor Control Training for the Shoulder with Smart Garments”, Sensors, doi:10.3390/s17071687

Q. Wang, P. Markopoulos, B. Yu, W. Chen and A. Timmermans, “Interactive wearable systems for upper body rehabilitation: a systematic review”, Journal of NeuroEngineering and Rehabilitation, 2017;14:20

Q. Wang, W. Chen, and P. Markopoulos, ”可穿戴传感系统在上肢康复中应用的研究与实践/ Application of Wearable Systems in Upper Extremity Rehabilitation: Research and Practice (review)”, Chinese Journal of Rehabilitation Theory and Practice, 2016; 22:12. DOI: 10.3969/j.issn.1006-9771.2016.12.022

Q. Wang, A. Timmermans, W. Chen, J. Jia, L. Ding, L. Xiong, J. Rong and P. Markopoulos,”Stroke Patients’ Acceptance of a Smart Garment for Supporting Upper Extremity Rehabilitation”, Journal of Translational Engineering in Health and Medicine (current status: accepted).

R. Bootsman, P. Markopoulos, Q. Qi, Q. Wang, A. Timmermans. “ Wearable technology for posture correction at work”, (current status: submitted to the International Journal of Human-Computer Studies).

Book Chapter:

Qi Wang, Wei Chen, Panos Markopoulos, “Smart Garment Design for Rehabilitation” in ICTs for Improving Patients Rehabilitation Research Techniques, Communications in Computer and Information Science,Vol. 515, pp 260-269.ISBN: 978-3-662-48645-0,2015;

Conference:

J. Du, P. Markopoulos, Q. Wang, M. Toeters and T. Gong. "ShapeTex: Implementing Shape-Changing Structures in Fabric for Wearable Actuation." In: Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction. ACM; 2018. p. 166–176.

J. Du, Q. Wang, L. De Baets, P. Markopoulos, "ZUOZI: Feedback of Postures for Shoulder Pain Treatment with Wearable Technology". PervasiveHealth'17.

Q Wang, Marina Toeters, Wei Chen, Annick Timmermans, Panos Markopoulos, "Zishi: a smart garment for posture monitoring", In Proc. Of the 34th Annual ACM Conference on Human Factors in Computing Systems (CHI'16), San Jose, CA, USA, 2016;

Q. Wang, "Designing Posture Monitoring Garments to Support Rehabilitation", In Proc. International conference on Tangible, Embedded and Embodied Interaction (TEI), Eindhoven, the Netherlands, 2016;

Q. Wang, W. Chen, A.A.A. Timmermans, C. Karachristos, J.B. Martens, P. Markopoulos,"Smart Rehabilitation Garment for Posture Monitoring" in 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Milan,2015;

Q. Wang, P. Markopoulos, W. Chen, "Smart rehabilitation garment design for arm-hand training" in Proceedings of the 8th International Conference on Pervasive Computing Technologies for Healthcare,PervasiveHealth '14, German,2014;

Q Wang, W Chen, P Markopoulos, "Literature review on wearable systems in upper extremity rehabilitation" in IEEE-EMBS International Conference on Biomedical and Health Informatics (BHI), Spain, 2014;

Other Publications

Sun, X., Lou, Y., Li, T., and Wang, Q. Designing Wearable Device-Based Product and Service Ecosystem. In Cross-Cultural Design Methods, Practice and Impact. Springer, 2015, vol.9180,108–115.

Tao, Y., Wang, G., Hong, Y., Wang, Q., Yao, C., and Ying, F. DrumGenius: bridging learning-gap with interactive musical instruments. Proc.

CSCW Companion’14, 241-244.

Wang, Q., Ying, F., Cai, J., and Cheng, Y. Designing to augment memory appreciation: The system of Mobile-light. TEI’13-work in progress.

Ying, F., Tao, Y., Wang, G., and Wang, Q. VisibleSound: Perceiving Environmental Sound with 4D Form. In Advanced Materials Research, vol.718, 1777-1781.

Ying, F., Cai, J., Wang, Q., et al. Cultural Design Method on Multi-Sensor Technology Design: A Case of Interactive Lamp Design. In Applied Mechanics and Materials, vol.321, 553-557.

Press:

“Live News”, in CCTV-13, Oct 31st, 2015;

Exhibitions:

Mind the Step, Dutch Design Week 15’

Global Grad Show, Dubai Design Week 15’

China Design Award 16’

Manifestations, Dutch Design Week 17’

Do (not) feed the makers, Dutch Design Week 17’

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Curriculum Vitae

Qi Wang was born on 21st of May 1988 in Handan, China. In 2010, She received her bachelor degree in Industrial Design (cum laude in Zhejiang Province) from Zhejiang University where she was recommended for admission to her master study, she obtained her master degree in 2013 with great interests in the field of Human-Computer Interaction. Subsequently, she was awarded the scholarship from Chinese Scholarship Council (CSC) for her PhD research in the Industrial Design Department in Eindhoven University of Technology (Tu/e) in the Netherlands. This thesis is the result of her research topic of "Designing Smart Garments for Rehabilitation".

She won multiple design awards including Red Dot Award and IDEA Award. During her master's education, she was also a design intern at Samsung design in Shanghai. Her work at Tu/e has been exhibited at Dutch Design Week 15 &17 and Dubai Design Week 15.

Qi Wang is married to Feng Xu and mother of Jingyi Xu.

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