WEARABLE PROPRIOCEPTION:
Designing wearable technology to improve postural instability in Parkinson’s Disease

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Abstract

This report covers the design research process and results of the 9-week Thesis Project I. A hands-on, Research Through Design approach led the project through an iterative process with a focus on creating functional prototypes and validation with experts to answer the research question: How could proprioceptive wearable technology assist in improving the quality of life for patients of Parkinson's Disease? Within this main question, focus points have been placed on designing for comfort (i.e. wearability) and well-being with attention to aesthetics. The project builds upon the theories of Design for well-being, Embodied Interaction and Wearable technology and is supported by research on proprioception, Parkinson's Disease, postural instability and sensory stimuli. The result is a series of models, sketches and prototypes and this report covering the process. The final concept and prototype is a system that monitors upper body posture and provides vibro-tactile feedback on strategically placed areas of the body to guide the patient towards the desired posture.
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1. Project outline

1.1 Introduction and background

We sense our movements and know how our bodies and its parts move in space thanks to proprioception. Voight & Cook (2001) describe proprioception as the sensorial processes involved in the consciousness of the spatial location of an individual, posture and movement. Or in an example, it allows us to walk (i.e. lift up our feet and move our legs) without looking down. When trying to maintain a particular posture or to perform a particular movement, this proprioception can be compromised by fatigue, inability to monitor it over a long time, or a damaged nervous system. Situated in physiotherapy, this damaged 'intrinsic feedback' undermines a patient's ability to check if the exercise is carried out correctly. In sports training, enhancing proprioception could prevent injury and improve results.

The initial opening for this research was to provide personalized feedback to patients (or athletes) by applying wearable rehabilitation technology. This could be a garment with sensors and actuators to provide feedback on movement and posture. The focus will be on comfort/well-being with attention to aesthetics. The result will be an integrated prototype that demonstrates a coherent and validated design concept.

Research in rehabilitation technology has for a long time, focused on robotic technologies (Brochard, Robertson, Medee & Remy-Neris, 2010). However, recent development in miniaturizing electronics and body area network technologies has generated interest in wearable rehabilitation technology (Wang, Chen & Markopoulos, 2014) Training for rehabilitation is directed at developing compensatory strategies and activating neural plasticity and recovery. Wearable systems with this intent may include a variety of components for: sensing (sensors, smart textiles), actuating and processing (actuators, wireless communication technologies, system controllers and processing units), and providing feedback and interactions (UI software, algorithms for data capture, analysis and decision making, interactive games) (Brochard et al., 2010) (Brewer, McDowell, Worthen-Chaudhari, 2007) (Bonato, 2009) (Patelopoulos, Bourbakis, 2010).

Wang et al. (2014) summarize: “...wearable systems are successfully used to support the gamification of rehabilitation training. A few such systems have been developed and there is already some positive evidence from clinical trials of limited scale. Still no randomized clinical trial has been reported, showing the need for expanding the empirical evidence regarding the effectiveness of this category of systems.” (p. 544). Their survey indicates that large technical
advances have been made in the last years with the arrival of wearable technology as a credible option for rehabilitation but that more attention needs to be paid to wearability and comfort.

When designing for well-being, it is important to develop a strong understanding for the perspective of the patient. Not to just focus on ‘fixing the problem’ from a medical perspective but to keep an eye out for the socio-cultural perspective as well. Developing a holistic view on the design of a proprioceptive wearable, for example how system properties must be balanced against form factors, has been of great importance in this design process.

1.2 Research focus

Preliminary research has been done on Parkinson’s Disease (henceforth mentioned as PD), specifically the postural instability and equilibrium problems that form one of the four main Parkinsonisms (the others are tremor, bradykinesia and rigidity). Recent evidence discussed by Ribeiro, Bizarro & Oliveira (2011) reveals that Parkinson’s Disease also causes alterations in proprioception and that “…disturbances in proprioceptive mechanisms directly affect postural control and the ability to calculate the velocity and amplitude of movement.” (p. 235) (Jacobs, & Horak, 2006). They conclude by stating that “The loss of postural control is the symptom that most affects the quality of life in PD.” (p. 238). Further elaborated, the postural instability greatly affects the patient’s conditions because it is linked to an increased risk of falling, immobility, hospitalization and the need for long-term care (Tan, Danoudis, McGinley & Morris, 2012) (Lamont, Morris, Woollacott & Brauer, 2011) which leads to an overall reduction of quality of life, in relation to health (Soh, Morris & McGinley, 2011).

Various posture-related studies indicate that patients of Parkinson’s Disease sway significantly more than healthy subjects. The cause of this is that PD patients are exceeding their limits of stability to a much larger extent (Menant, Latt, Menz, Fung & Lord, 2011) further supporting the hypothesis that they have difficulties appropriately scaling postural reactions because of a proprioceptive deficit (Beckley, Bloem & Remler, 1993).

The research question is:

How could proprioceptive wearable technology assist in improving the quality of life for patients of Parkinson’s Disease?

Within this main question, focus points have been placed on comfort (i.e. wearability) and well-being with attention to aesthetics. As for the design research process, it will be an
iterative one with a focus on developing working prototypes as a part of the route to
discovery.

1.3 Collaborations

With a focus on Parkinson’s Disease it was essential to get in touch with local experts and
possibly patients to validate the ideas. A collaboration was set-up with physiotherapists Erik
Löfgren and Malin Olsson from Abels Rehab (part of Primärvården Skåne) who were also
able to arrange a meeting with a patient for our second session. Furthermore, an important
partner for expert validation was found in the duo Eva Bramell-Risberg and Cecilia Winberg
from private healthcare instance Neuro Rehab.

1.4 Ethical considerations

In the design process, different people (i.e. both healthy individuals as patients) have been
involved in the evaluation of the concept and the prototypes. The integrity of the participants
is of great importance. Therefore, ethical considerations include:

• Voluntary participation: People participate free from coercion. Participants are free to
withdraw at any time without negative impact for them. Explanations are not required.
• Informed consent: The participant is fully informed about the evaluation being conducted
and is aware of the purpose of the project and how the findings might be used.
• Confidentiality: Identifying information is not made available and is excluded from any
report or publication.
• Do no harm: The evaluation process should not harm in any way (unintended or otherwise)
the participants. Harm is understood as both physical and/or psychological.

1.5 Methodology

To quote Obrenovic (2011) “Design problems are often full of uncertainties about both the
objectives and their priorities, which are likely to change as the solution implications begin to
emerge. Problem understanding evolves in parallel with the problem solution, and many
components of the design problem cannot be expected to emerge until some attempt has
been made at generating solutions.” (p. 57). Furthermore, Gaver (2012) states that “the
synthetic nature of design allows for richer and more situated understandings than those
produced through more analytic means.” (p. 942) and that the role of theory should be seen
as one to annotate design examples rather than to replace them. Therefore the Research Through Design methodology has been used as a way of thinking for this project. Using the design process to deepen the understanding about the design context and problem but approaching the design process from a ‘making’ as well as a ‘thinking’ perspective. Following the idea introduced by Schön (1983) that design is part of the reflective practice to reflect both on action and for action. Reflection has been defined as a “mental process that occurs before, during and after situations with the purpose of developing greater understanding of yourself and the situation so that future encounters with the situation are informed by previous encounters” (Sandars, 2009, p. 686).

The approach of this project had a highly iterative character, with succeeding prototypes each addressing the different design decisions, and enabling validation by experts in every phase, as well as posing new questions for the next iteration. This is what Schön mentions as reflective conversation with the material (e.g. sensors, micro processors, code, form factors etc.) which is significant for the knowledge construction in this design process. Alternative to doing a field study and then deciding what to design, the preference was given to do design work in parallel with learning on Parkinson and proprioception and what designed technology can do in relation to that. A reflective conversation where one learns through the designing of prototypes and where the practice of making was a road to discovery. Additionally, cooperation with experts as part of the evaluation and iteration was crucial for the accuracy and validity. This point also stressed the importance of making prototypes as they function as great conversation pieces and fueled the discussion, also, it’s not unimaginable that thanks to the fact that the physiotherapists were impressed by the first lo-fi prototype, their respect was gained and they made their best effort in arranging the next meeting with a patient.

1.6 Literature review

With the possibility to design for people with Parkinson's Disease as the main target group, more research had to be done. To get a better understanding of the pathology, from a neuromechanical level to a socio-cultural level. To discover the relationship between proprioception, postural control and PD. And, to learn from wearable systems in rehabilitation in general. This is a summary of the most relevant, inspiring or otherwise interesting findings.

1.6.1 Design for well-being

There is a need for design engineers offering creative solutions in the form of innovative products and technologies that benefit society. Larsson, Larsson, Leifer, Van der Loos &
Feland (2005) argue why it is crucial to qualitatively assess both the impact on the potential market and on 'quality of life' afforded by the designed innovation. Their definition is as follows: “Design for Wellbeing offers a perspective on life quality that goes beyond the traditional scope of assistive technology in that it aims to help people make a transformation from an actual state of being to a desired state of being - regardless of ability level.” (p. 1). In a project designing for health care it is important to develop a strong understanding for the perspective of the patient. It is easy to focus on 'fixing the problem' from a medical perspective but often, there are opportunities found in the socio-cultural perspective that are seemingly small but in effect, have the biggest impact on the perceived well-being and quality of life.

1.6.2 Embodied interaction

If we look at embodied interaction in the design process, Dourish (2001) defines embodied interaction as “the creation, manipulation, and sharing of meaning through engaged interaction with artifacts.” (p. 126). In this project, designing a smart wearable for healthcare purposes, the form factor and exploring the material can be of equal importance as the functionality. It is something personal, can be quite expressive and is worn close to the body. In extent to this, Vallgårda & Sokoler (2010) argue how computers, in principle, can be understood as a material for design and how they can be included in the form giving process. They propose a material strategy that emphasizes the expressional potential of computers. In essence “the strategy is to design computational objects through ongoing negotiations between form and function through direct manipulation of computational composites.” (p. 12).

Performing bodily movements and developing bodily skills can be both challenging and very rewarding. In the past research has been done on the semantics of movement of products (through physically moving parts) and the aesthetics of actions. An overview of 20th century commercial products will show how design increasingly neglected our perceptual motor skills, while burdening our cognitive abilities. A more refreshing conceptualization of 'human nature', that has strong connections to the inclusion of movement in interaction design, is the philosophy of 'Embodiment', which positions the body at the foundation of our existence. “Embodiment argues for a re-appreciation of the body, and that meaning in interaction is best understood as being created during bodily interaction.” (Djajadiningrat, Matthews & Stienstra, 2007, p. 658). Where this touches upon the project is in the area of embodied knowledge. For example, in physiotherapy meaning is created during actual, physical interaction and can not be replaced by extracting it from charts.
1.6.3 Wearable technology

What can be understood as wearable technology is best defined by Steve Mann (2003) who is often seen as the pioneer in this field: "Wearable computing is the study or practice of inventing, designing, building, or using miniature body-borne computational and sensory devices. Wearable computers may be worn under, over, or in clothing, or may also be themselves clothes." (para. 1).

Research in rehabilitation technology has for a long time, focused on robotic technologies (Brochard et al., 2010). However, recent development in miniaturizing electronics and body area network technologies has generated interest in wearable rehabilitation technology. Wang et al. (2014) argue that, technological advancements have enabled wearable sensing of motion and posture to be exceeding that of human observers. For example, the angular resolution that humans can perceive lies between 2º and 6º, which illustrates the potential of technology, especially in medical and rehabilitation context where monitoring and feedback relies on therapists.

In their survey of existing products, systems and related services, Wang et al. (2014) further discuss what they consider important in the development of smart wearables for healthcare, in their case focussed on upper-extremity rehabilitation but transferable to PD regardless. A few wearable systems to support rehabilitation training have been developed and clinical trials of limited scale prove value, showing the need for expanding empirical evidence with regards to the effect of these systems. Furthermore, increasing attention needs to be paid to comfort, and wearability.

Park & Jayarman (2003) explain the role of smart wearables in addressing the challenges in healthcare. They do this with reference to the Wearable Motherboard also known as Smart Shirt (Georgia Tech, 2015). Initially funded by the U.S. Navy, Georgia Tech led the research that according to them resulted in the first “intelligent” garment for the 21st century. The original shirt uses optical fibers to detect bullet wounds and reads the vital signs of its wearer but later, the product developed towards healthcare purposes, monitoring vital signs in an unobtrusive manner. They conclude “By enhancing the quality of life, minimizing “medical” errors, and reducing healthcare costs, the patient-centric wearable information infrastructure can play a critical role in realizing the future healthcare system envisioned by the Institute of Medicine.” (p. 48).

What these sources fail to touch upon, is how wearable technology can, and should, be something more than just computers that you can wear as clothes or garments. There is a form factor at play, they should look and feel nice. What will be discussed in more detail later, is that nobody, Parkinson’s patients included, likes to be seen as damaged or invalid when in
public situations. Wearable technology should not make them into walking circus attractions but instead be subtle and discrete where possible or alternatively, a thing of beauty that you are proud to be seen with.

1.6.4 Proprioception

Voight & Cook (2001) describe proprioception as the sensorial processes involved in the consciousness of the spatial location of an individual, posture and movement. They further elaborate that postural control and movement ultimately depends on the orchestrated feedback of contracting and stretching muscles, and the corresponding response activities in the spinal cord. Bodily movement therefore, depends on the speed and precision with which mechanoreceptors – positioned in the muscle fibers, signal these adjustments. Stimuli from the skin also play a part in the consciousness of static and kinetic activities (e.g. touch, (air) pressure, temperature, etc.). Whether or not these receptors are properly functioning as part of the proprioceptive system may be of importance for interpreting the alterations in sensorial processes and perception found in people with PD.

Recent evidence, indeed, shows that the disease causes alterations in proprioception. “Disturbances in proprioceptive mechanisms directly affect postural control and the ability to calculate the velocity and amplitude of movement, suggesting that these alterations are related to the motor symptoms of PD.” (Ribeiro et al., 2011, p. 235). Various studies (Klockgether, Borutta, Rapp, Spieker & Dichgans, 1995); (Seiss, Praamstra, Hesse & Rickards, 2003) indicate that PD patients show difficulty performing movements relying on proprioceptive integration (e.g. reach-and-grab actions or estimating upper-extremity position with the eyes closed). These symptoms suggest a gap or limitation in the proprioceptive capacity of PD patients.

Seiss et al. (2003) further explains that the cortical degeneration of sensorimotor and premotor areas (slowly 'shutting down' parts of the brain) is what seems to make the interpretation of sensorial information problematic. This is what obstructs sufficient proprioceptive feedback and, in turn, leads to the patient falsely estimating his position in space, miscalculating the necessary speed, causing bradykinesia (slowness of movement). Similarly, an impairment to the extrapyramidal system (the neural network that causes involuntary reflexes and movement, and regulation of movement (i.e. coordination)) can lead to falsely estimating the quantity of sensory stimuli, causing automatic, unconscious and unnecessary movements (dyskinesia). What will be interesting to see is if, how and to what extent external sensory stimuli will effect the proprioceptive capacity of PD patients.
1.6.5 Disease definition and characteristics

Parkinson's Disease is a progressive neurodegenerative disorder that affects dopaminergic neurons in the Substantia Nigra, part of the Basal Ganglia located at the base of the forebrain. It is the second most frequent neurodegenerative disorder after Alzheimer's Disease and although it is more prevalent in the elderly society it also affects young individuals (Alexi, Borlongan, Faull, Williams, Clark, Gluckman & Hughes, 2000).

It is only when dopamine levels in this part of the brain (the striatum, specifically) already have dropped with 80% that compensation mechanisms become insufficient to contain the deficit what leads to the exterior manifestation and first diagnosis of Parkinsonisms. (Ribeiro et al., 2011). This is what makes it extremely difficult to discover what causes P.D. and how to cure it.

The motor-skill disturbances in PD is what greatly affect the patient’s quality of life and occur even during the most basic day-to-day tasks as sitting, walking and writing. Fair performance in any of these activities call for good integration of sensory inputs and motor responses, which in essence is what proprioception is all about. According to Ribeiro et al. (2011) however, “The loss of postural control is the symptom that most affects the quality of life in PD.” (p. 238).

1.6.6 Postural instability

Losing postural stability greatly impacts the life of patients because it is associated with immobility, an increased risk of falling, hospitalization and the need for long-term care (Tan et al., 2012) (Lamont et al., 2011) which overall, reduces the quality of life in relation the health (Soh et al., 2011).

Posturographic studies done by Menant et al. (2011) show that people with PD sway significantly more than healthy subjects because they tend to go beyond their limits of stability. Which is in line with earlier neurological research by Rocchi, Chiari, Cappello, Gross & Horak (2004) who found that patients often have difficulties keeping the body still and additionally recognize that PD may decrease the ability to use the legs to recover from imbalance through compensatory steps.

Volpe, Giantin & Fasano (2014) point out, that this supports the hypothesis that an important role is played by an impairment in appropriately scaling the muscle response in reaction to disruptions in balance. Concluding, a deficit in proprioception may be the cause of underestimating the body position and reducing movement amplitude.
1.6.7 Sensory stimuli

Nolano, Provitera, Estraneo, Selim, Caporaso, Stancanelli & Santoro (2008) presents evidence from a quantitative sensorial study with PD patients that shows increased tactile- and thermal thresholds as well as a reduction in pain perception. This is explained by a significant loss of epidermal nerve fibers and Meissner corpuscles (the mechanoreceptors just underneath the skin responsible for sensing touch and low-frequency (50Hz) vibration). One part of the explanation of reduced proprioceptive capacity in PD - reduced skin sensitivity, which normally strongly contributes to proprioception.

Still, when the skin is exposed the external stimuli, a response is generated in the Basal ganglia, which plays a vital role in the regulation of processing sensorial input in the thalamus. A proprioception-related study by Nakashima, Nitta & Takahashi (1992) revealed that sensorial potential triggered in the parietal cortex (responsible for integrating sensorial information) of PD patients in generally normal. This validates the perception that there is no damage to the sensorial system conduction in PD patients.

Externally applied vibration appears to be a strong impulse (especially muscle spindles endings are sensitive) to convey proprioceptive queues to the central nervous system that regulated the spinal reflexes excitability as well as posture and muscle response as concluded by Volpe et al. (2014) and supported by various studies.

1.7 Related work

To get a better overview of what's already out there, research is performed on prior works that have been done in the field of Parkinson's Disease, postural (in)stability and proprioception. What follows is an analysis of the most interesting products, systems and/or related services.

EQUISTASI

A vibro-tactile sticker with nano technology, that can be applied to the skin of an affected muscle zone (see fig. 1). Equistasi (Volpe et al., 2014) then self-produces a mechanical focal vibration when the slightest thermic variation occurs. This is interesting because during the development of this product, a lot of research has been done on the beneficial effects of externally applied vibrations on muscle zones. It interacts with the mechanical receptors, the Golgi tendon organs and the neuromuscular fusion. The stimuli produced by the vibrations...
transmit information to the central nervous system: the upper motor centers are stimulated by vibrations, in order to obtain a better performance of the nerve commands that control muscular recruitment.

**LIFTWARE**

LiftLabs developed *LiftWare* (Liftware, 2015), a motion stabilizing piece of cutlery (see fig. 2) that actively counteracts tremors thus allowing PD patients to feed themselves without spilling the contents of the spoon, fork or knife before it can reach their mouth. Very inspiring because it is using everyday optical stabilizing technology we can find in our smartphone cameras to make a simple product that can have a major impact on the quality of life of PD-patients. Basic day to day operations, like being able to feed yourself, is something easily taken for granted but the degree of self-efficacy (one's own ability to complete tasks and reach goals) is strongly related to perception of self-worth and overall happiness.

**LASERCANE**

After the success of the LaserWalker, Accessible Design released the *LaserCane* (Introducing the LaserCane, 2015), where from the top of a walking cane, a red beam shoots across the path of travel and helps the patient walk considerably faster (see fig. 3). Again, it is interesting to see something seemingly simple have a great impact. The visual queue has large enough cognitive effect on the patient helping them to move their legs when ‘freezing’ (a state where
the gait comes to an involuntary and abrupt halt) or when shuffling of the feet is an issue. It is important to note that queueing is an important strategy for PD-patients to cope with these problems and what method of queueing is effective differs from person to person.

**ARC PEN**

Dopa Solutions created *ARC* (ARC therapeutic vibration pen, 2015), a pen containing a high frequency vibration motor that stimulates the correct muscles in the hand of the PD patient (see fig. 4), resulting in a 86% improvement in writing. What is fascinating is that opposed to the LiftWare cutlery, that neutralizes the tremors, the ARC pen actually eliminates the tremors in the hand to a large extent. Again, relating to the basic day to day operations like handwriting a post card or shopping list, the ARC pen proves it's worth in re-enabling patients to do so, which greatly influences the quality of life in a positive way. Additionally interesting, is how vibration at just the right frequency can have this stimulating effect.

**VAL SIMULATOR**

At the University Medical Centre st. Radboud, researchers of the Rehabilitation and Neurology Department developed an unique and highly advanced *Fall-Simulator* (UMC St Radboud ontwikkelt unieke valsimulator, 2015) (see fig. 5) to study the balance reactions and muscle activity in people who are brought in misbalance. The yearly amount of people being hospitalized after a fall, and the resulting medical costs as part thereof, are staggering. Studying how and why people fall, therefore, is an interesting and societal relevant topic. as solutions could have great impact on peoples lives and rising medical costs.
REMPARK

The Technical Research Centre for Dependency Care and Autonomous Living is developing REMPARK (REMPARK, 2015), a wearable personal health system (see fig. 6) that monitors and quantifies the symptoms of the disease associated with motor status. As there are still so many questions about Parkinson’s Disease unanswered, it can be interesting to make use of the qualities of the quantified self in order to gather more evidence regarding, for example, the progression of the disease or the effect of specific medication. Additionally, they aim to include a functionality where your personal physician can consult with you from a different location.

LUMOBACK

Lumo Body Tech developed a belt worn around the lower back and core that helps you to sit up straight when you slouch in your chair (LUMOback, 2015) (see fig. 7). The measurement unit on the back senses your lower back posture and starts vibrating whenever you are not in the optimal seated position. Furthermore, it measures how long you sit and shows you different statistics through the accompanied app. The LumoBack was successfully funded on Kickstarter within a few days, showing the publics interest in posture coaching. This product would be less suitable for PD-patients because it has some limitations (e.g. only senses lower-back slouching) and has a focus on the seated office environment.

ROTATIONAL SKIN STRETCH

As an alternative to vibration, other tactile input methods were researched. The most fascinating being Rotational Skin Stretch that is studied by Stanford University (Bark, Wheeler, 2008).
Premakumar, & Cutkosky, 2008). Their prototype simulates the motions and sensations of placing two fingers on the skin and rotating them together (see fig. 8). They found this method allows for the accurate display of degrees of rotation, meaning a larger input scale than is possible with, for example, vibration. It could function as a proprioceptive feedback mechanism for prosthetics.

1.8 Summary

The idea appears to be fruitful, feasible and novel in the field of Parkinson’s Disease and has potential to stretch out into other fields (e.g. medical, sports, performance) as well. The literature supports the validity of the idea of proprioceptive enhancement for PD patients through a wearable system and in the product survey no identical system has been found. From the literature review, a deeper understanding of the pathology and its problems was formed, as well as some insights in how design and technology could be of value in this context. Parkinson’s Disease is a wide-spread and complex pathology where different problems and different patients require different solutions. The related work section therefore, showed diverse examples with interesting elements but none of them offer real value for the problems faced with postural instability. The next step was to further define the concept and to develop a first prototype that can be used to validate the concept with experts in the field of PD such as physiotherapists and/or researchers.
2. Process

2.1 Design Pressure Cooker

In the first week of the thesis project, even before the research phase, a 'Design Pressure Cooker' was organized. A design method in which you go through all the phases of the design process in just one day. Research, Ideation, Conceptualization, Prototyping, Validation, Evaluation in only 6 hours effectively. By already completing a full design cycle so early on, the design domain is explored in each of the different phases and the interconnections between them are discovered. The Design Pressure Cooker allows for; sharpening the design proposal; making a better-informed planning and; improving the performance the second time you go through the phases by drawing lessons from the failures and successes that are faced in the Pressure Cooker. The outcomes, and learning experience as part thereof, are presented and discussed informally among peers.

RESEARCH & IDEATION PHASE

A search was done on 'Proprioceptive Wearables' with as primary goal to gain inspiration for the ideation part of this Pressure Cooker. What attracted attention most was a wearable proprioceptive stabilizer (Equistasi) that emits focal mechanical vibrations and is applied in many different fields, namely Orthopedic rehabilitation, Neurological rehabilitation, Sports, Pain relief, Correct posture and Elderly. Equistasi is composed exclusively out of fibers with applied nanotechnology that makes it sensitive to the smallest thermic variation that the product transforms in mechanical energy self-generating focal vibration. It comes in the form of an adhesive patch that is applied directly onto the skin of the affected muscle zone, preferably by a physical therapist.

Vibrations produce stimuli that transmit information to the central nervous system (CNS). More research was done on the CNS which shifted the research towards Parkinson's Disease (PD) or more specifically 'Parkinsonisms' – the main motor symptoms that are associated with PD, among others. One of these symptoms is postural instability, leading to impaired balance and frequent falls (Yao, Hart & Terzella, 2013) and, often as a consequence of this, bone fractures (Jankovic, 2008). Recent evidence indicates that PD also causes alterations in proprioception (Ribeiro et al., 2011) which made it into the main target group for this Pressure Cooker.
CONCEPTUALIZATION PHASE

The concept is to measure tilt of the hip and give tactile vibration feedback if the tilt values go beyond a specified value. The preliminary hypothesis is that PD patients develop a proprioceptive deficit that limits their capability to maintain their balance and/or timely intervene before a fall. Furthermore, vibro-tactile feedback could fill in this gap in proprioception. More research has to be done on this topic if the concept proves value.

PROTOTYPING PHASE

A low-fi prototype is made using a regular belt, two tilt sensors and two vibration motors connected to an Arduino Uno. The two tilt sensors are attached to the belt in opposing angles just beyond horizontal. When the belt is placed around the hip, this results in 3 measurable positions: centered balance, exceeding left tilt value, exceeding right tilt value. The values, or sensitivity can be adjusted by altering the angle of the tilt sensors on the belt more towards or away from the horizontal. When exceeding one tilt value, the vibration motor (placed on the inside arch of the foot) on the opposing side turns on, warning you to distribute your weight back to this point.

VALIDATION PHASE

To validate this concept without PD patients, healthy test subjects (n = 4) are asked to (1) balance on one leg, to simulate the postural instability, and (2) close their eyes, to simulate a proprioceptive deficit. They perform this task with and without the prototype and are asked to evaluate the effect of the prototype. All of them found the vibro-tactile feedback helpful in maintaining their balance.
EVALUATION PHASE

Although the theoretical grounding of the concept was insufficient at this point, the practical validity seemed to be promising. More research, a higher quality prototype and more extensive user testing, also involving PD patients, was needed if this concept was to be pursued further. An interesting outcome was that the same technology might be useful for ballet dancers, who have to learn to maintain their hips in a horizontal position while performing certain exercises. This could have been an alternative target group for this concept.

SUMMARY

Pushing yourself to design something so early on in the design process is always challenging, but in the end, the pressure cooker gave a clear direction to pursue further. Even when this direction is fragile and the foundation is still unstable, it was a great starting point for an iterative design research process. Many changes have been made in the iterations that followed but the hands-on approach was an eye-opener to the opportunities.
2.2 Concept development

INITIAL DESIGN SKETCH

Figure 10: Initial design sketch.

To bring the concept to life and to have something to put up for discussion a first design sketch was made. Drawing out the details of the design forced deeper thought into the concept and already lead to some interesting insights, which illustrates the benefits of a research through design approach.

What you see here is an 'all-in-one' waistband that is wide and of a soft material for comfort and is easy to put on plus size-adjustable through a velcro closing on the front. The backside holds a pocket for containing the Arduino, battery and an accelerometer for measuring the lateral tilt of the hips. When exceeding the thresholds in lateral flexion, a vibration motor attached on the opposing side will start vibrating.

Insights are to have the vibration motors placed in a removable/replaceable pocket so that: 1) the position of the vibrations can be easily altered to improve experimentation, and 2) from a
hygiene perspective, the belt would become washable. Secondly, LED's would be added in line with the vibration motors for debugging purposes (also visualizing when the tilt threshold is exceeded when someone else is wearing the system).

After discussion, the decision was made to also include forward/backward tilt as the forward arching and accompanied instability is also a common sight in Parkinson's Disease.

2.3 Prototyping I

DESIGN

The dilemma was between buying some kind of belt or making one from scratch. Diverse options were considered, ranging from running belts to fitness equipment to pregnancy support, but all of them required a substantial financial investment. The decision was made somewhat in between:

• An ordinary waist belt for holding the Arduino, potentiometer, LED's and battery.
• A fabricated chest band for positioning the accelerometer higher onto the body.
• And, improvised knee bands (from socks) to attach the vibration motors to different positions on the leg.

As opposed to the first sketch, it was decided to place the accelerometer higher on the body (chest) because after some body storming and analyzing video footage from PD patients, the conclusion was drawn that the tilt of the hip is not a good indicator for postural instability and an alerting for an increased risk of falling.

Next, 4 LED's are distributed on the waist belt to indicate forward, backward, left and right tilt. A potentiometer is added to adjust the thresholds in all four directions and thus managing the sensitivity of the system.

Finally, after some experimentations it was found that the combination of these mini vibration motors and the positioning on the hip resulted in low noticeability and a disconnection from logic regarding to how you should act upon vibration alerts. The position on the backside of the knee (kneecap) is fruitful for it is both sensitive and it appeals to the logic of human reflexes and balancing techniques.
Figure 11: First prototype (l) and a close-up of the technology (r).

TECHNICAL COMPONENTS

1 Arduino Uno
1 ADXL337 3-axis accelerometer ±3G (3.3V)
1 Potentiometer
4 LED’s (red)
2 Mini vibration motors
1 Battery (9V) + 2.1mm jack connector
CODING

All coding was done in Arduino. Initial example sketch 'ADXL337_example.ino' from author Jordan McConnell was used to read out accelerometer data. From there new code was written and inspired from various online examples. Version 1 was able to measure tilt on the x- and y-axis (4 directions) and actuate the 4 corresponding LED's and 2 vibration motors for left and right tilt.

TROUBLESHOOTING

Experimenting with the prototype was of great value to take the concept a step further. Feeling the strength of the vibrations and the sensitivity on the skin or garments, experiencing the reactions of sensors and actuators but also practical matters like putting the system on and moving around all led to new discoveries to investigate and new issues to solve. The following 'quick fixes' were made from the 'conversation' with the prototype:

In version two, a potentiometer was added to be able to easily adjust threshold sensitivity (i.e. how many degrees of upper body tilt before the system kicks in). Being able to quickly adapt how the prototype functions creates the flexibility to experience and discuss many different settings and variables, which can be very fruitful especially early on in the design process. Even with the sensitivity decreased, there were some false positives. In the version that followed, the raw accelerometer values were smoothened (by code) to make them more stable. In version four, the code was further adjusted to compensate the changed orientation on the user back as opposed to laying flat on the table. After that, the prototype worked fine... on the ground floor. Because the accelerometer's tilt function works with gravitational forces, the read-out is slightly different on the 4th floor. On top of that, because the chip that is being used is relatively inexpensive, measurements starts out slightly different each time. Therefore, version five included a calibration method: After reset, 5 seconds of accelerometer data are recorded to determine the 'neutral' position. This encompassed vertical displacement as well as enabled to set different 'neutrals' (i.e. not everyone is able to stand perfectly straight). Finally, it was found that when on the edge of the thresholds, values are still fluttering slightly. The last version of the code (for now) added a more advanced smoothing method for even more stable readings from the accelerometer.
2.4 Validating & Evaluating I

EXPERT VALIDATION: ABELS REHAB

To validate the concept, a meeting was organized with two physiotherapists at ‘Abels Rehab’ in Malmö. Together they share many years of experience working with people with Parkinson’s Disease or Parkinsonisms, both in individual- and group sessions on a regular basis. Part one of the meeting was a duo interview to allow them to exchange thoughts and complement each others answers. Questions ranged from their activities as physiotherapists and the materials that are used to, more narrowed down, symptoms as postural instability, gait impairment and specific patient cases. In the second part of the meeting the designed prototype was experienced by the physiotherapists opening up for a discussion about the concept, the current prototype and future improvements. The overall impression was very positive and the concept has been successfully validated by these experts. They were convinced of the practical use of the design for people with P.D. and a trial session with an actual patient is scheduled. What follows is a summary of the most interesting outcomes:

Abels Rehab, as primary care instance, first provide information to people diagnosed with P.D. or Parkinsonisms and explain what it might lead to. They give instructions and exercises to do at home. In the later stages patients train in groups and individually to work on mobility, balance and flexibility. Group therapy is considered most beneficial because of the social aspect and the increased motivation that comes from that. Therapy involves different exercises in stations, for example: TRX-training, rubber resistance bands, treadmill, steps and bike ergometer.

It is re-affirmed that monitoring forward tilt in addition to sideways tilt would be interesting. The vibrations could serve as a reminder to straighten up the body. This is especially important in the early stages of the disease where the flexion of the upper body is discrete and often not noticed by the patients but something the physiotherapists steer on continuously. Also, patients in the early progression are more often still cognitively intact.

Patients in the later progression of the disease often suffer from ‘Camptocormia’ (an abnormal posture with distinct flexion of thoracolumbar spine that decreases in the horizontal, flat position (Azher & Jankovic, 2005) (see fig. 12a)) and/or Pisa syndrome (chronic or sub chronic lateral flexion of the upper body (Yokochi, 2006) (see fig. 12c,d)). The proposed design could effectively postpone and possibly decrease the severity of Camptocormia and Pisa syndrome in Parkinson patients.
One of the other parkinsonisms that is worth looking into is the ‘freezing’ of the legs and reduced stride length, causing the shuffling of the feet or a inflexible state in which the patient can not initiate any walking movement. Sensory input, such sound (e.g. beats/rhythm) or visuals (e.g. laser projections), can be used as queues to re-instigate movement. Vibrations might be of use for this as well as sometimes tapping of the leg is a successful strategy too.

For the placement of the vibration motors in the case of forward/backward movement, it is advised to have a look at the so called hip- and ankle-strategies for balancing (Horak & Nashner, 1986) to correlate the position of the vibration to the muscle zones that are to be used to correct the posture.

Figure 12: Illustrations and photographs of cases of Camptocormia (a) and Pisa Syndrome (c,d). (Doherty, van de Warrenburg, Peralta, Silveria-Moriyama, Azulay, Gershanik & Bloem, 2011)
EVALUATION

The first prototype allowed for the bodily experience of the design and interaction and was an essential element in the validation with physiotherapists working with patients with Parkinson’s Disease. Thanks to the prototype, the conversation went beyond theory and abstract visions. It also captured the interest of the experts to pursue the collaboration further. Where the design in the first iteration was mainly focussed on the technology, the second iteration will focus on design, technology and functionality in parallel.

Within design, increased attention will be placed on comfort and wearability. The chest-strap that holds the accelerometer is slightly uncomfortable and will get annoying over time. One possibility for improvement is to make the technology into a clip, so that in the first place, women can attach it to their bra strap. Men would either still have to wear (a more comfortable) chest-band or when the technology will be small and light enough, attach it to a under shirt that is worn close to the body (to keep the sensor stable). Similarly, the waist unit which is now attached to an extra belt can be clipped to the existing belt or to the back of the pants or skirt.

Regarding technology, making the system (more) wireless will greatly improve the wearability by cutting the time that is needed to put the system on and removing possible constrictions and limitations of mobility. Additionally, it will give the prototype a more secure and robust look in the eyes of the user, which allows for more worry-free and therefore better user testing. Next to wireless connectivity, some steps have to be taken to decrease the size and weight of the prototype. Making it more comfortable and easy to wear.

On functionality, improvements can be made by including vibration feedback for forward-flexion. Next, the calibration process could be made faster and easier for the user. Additionally, it will be interesting to look into added functionality in the form of: quantifying data for the user insight and for research purposes, registering and assisting for help if the user does fall over, and finally, integrating a ‘gait coach’ to improve walking and offer a solution for the ‘freezing’ phenomenon in Parkinson’s Disease.
2.5 Prototyping II

ANKLE- AND HIP STRATEGIES

For the future placement of the vibration motors research has been done on so called hip- and ankle-strategies for balancing (see fig. 13) as mentioned by one of the physiotherapists. The decision is made to first experiment with placement on the Paraspinals to re-adjust forward arching to an upright position because this muscle group is used in the (more subtle) ankle strategy when swaying forward. Plus, together with the Abdominals, are the most responsible to correct and hold a correct upper-body posture. The Paraspinals (lower back) turn out to be sensitive to externally applied vibrations without being uncomfortable. The third vibration motor will then be placed inside the waist module that is attached to the back outer side of either the waist belt, pants or skirt.

Figure 13: Primary Stabilizing Muscles for during Anterior/Posterior Postural Sway [Online image]. Retrieved April 29, 2015 from http://media.lanecc.edu/
FORM AND SENSE

To protect the electronics and improve the perception of the prototype, casings will be designed for the chest and waist unit. First step was to measure the required space for the electronics and start shaping the form around that. The initial exploration was done on paper: A simple casing designed by rounding off the shape around the electronics space. The result is, for one, very boring, but on top of that resembles the trend that can be seen in health care products (see fig. 14):

Figure 14: First explorative sketch of the casing.

rounded, soft edges and often shaped out of white plastic. Giving an overall harmless and benign look. However, people in general do not want to be seen as sick, weak, handicapped or incapable. And neither should they have to nowadays. Look for example how optical eyeglasses transformed from medical accessory to fashion accessory.

The aim then, is to make a medical accessory look cool and desirable. More a high-tech wearable than something that showcases your disabilities. Maybe eventually, it can be something you wear with pride, like a piece of jewelry.

Different explorations are done on shaping geometric forms. 2D sketching (see fig. 15) feels limiting because it doesn't let you experience the tactile feel and proportionality. Clay on the other hand, allows for sculpting new shapes but every time you touch it the sharp cut edges
become more rounded. Foamcore plates are a great modeling material but doesn’t easily lend itself for very complex shapes. Modeling foam allows to sculpt the model from one block but fine detailing by hand sanding takes ages. Decided is to create a form skeleton from wooden sticks connected by blu-tack (reusable adhesive). Additionally, paper folding is used as a technique to further explore geometric shapes (see fig. 16).

Figure 15: Explorative sketch of a geometric design casing.

Figure 16: Geometrics explorations through wooden sticks (l) and paper folding (r).
Next, a 3D model was made in the computer. Inspired by a diamond cut, the model has a lot of small facets, hoping that the way the light catches the 3D printed plastic part would give an interesting glistening effect. However, it turned out that the model was too detailed (too many, too small facets) to be well visible in the printed version. (see fig. 17)

Eventually, two 3D models are made in the computer and printed in black plastic (PLA) using a 3D printer. The larger, waist module is brushed with clear high gloss varnish in an attempt to make it more resemble a polished gem stone. The smaller, chest module was untreated (see fig. 18). It is difficult to apply the varnish without flaws (e.g. visible brush strokes, air pockets). The natural look and feel of PLA is luxurious enough. Public opinion is in favor of the untreated model. The decision is made to go with untreated PLA.

![First 3D model with too small facets (l) and the 3D printed result (r).](image1)

![Improved 3D models for (smaller) chest and (larger) waist unit (l) and their 3D printed results (r).](image2)
FORM PHILOSOPHY

Gem stones or crystals have been believed to hold healing powers or give supernatural abilities (see fig. 20). Consequently, these gems are processed into wearable jewelry (see fig. 19), to be worn close to the body to feel its effects. Similarly, the designed wearable technology in this project would enhance the wearers proprioceptive capabilities, or give the power to sense and actuate on minute postural imbalances that could otherwise lead to chronic instability and spine deformity. Furthermore, the aim for a gem-like aesthetic allows for a more beautiful wearable that can be worn on the body with pride and dignity.

Figure 20: Amethyst (l) and Quartz (r) processed into wearable jewelry. BRIT+CO (2015). An Illustrated Guide to Gemstones [Online image]. Retrieved May 23, 2015 from http://www.brit.co
Figure 19: Gemstones and corresponding special powers [Online image]. Retrieved May 23, 2015 from http://www.ringswithlove.com/
SAFETY PRECAUTIONS FOR DBS SYSTEM

Because the proposed patient for user testing carries an internal system for Deep Brain Stimulation (not uncommon in PD-patients) some research has been done on safety precautions regarding the wearing of electronic components on the body and wireless communication signals.

In terms of electronics there are warnings/precautions for cardiac pacemakers or therapies, cardioverter/defibrillators, external defibrillators (200-1700V), ultrasonic equipment, electrocautery, or radiation therapy. The Arduino, operating on just 5V, is in a whole different range.

In terms of wireless communication signals: Theft detectors and security screening devices may cause stimulation to switch ON or OFF, and may cause some patients to experience a momentary increase in perceived stimulation but this goes for magneto-harmonic and acousto-magnetic systems that are powered at around 100Hz. The systems that work on radio frequency (low power, MHz-range) such as bluetooth and XBee/ZigBee are considered safe.

Expert advice from the contact person for the DBS system is still pending...

EXPERT MEETING WITH TONY OLSSON (PROTOLAB)

To explore the possibilities for making the prototype (more) wireless, a meeting with Tony Olsson from the K3 ProtoLab was set to gather his expertise on wireless technology and wearables. Without a clear winner, the following technologies were discussed and because they can be seen as a knowledge contribution, particularly for future iterations of this project, are added in this part of the thesis as opposed to disappearing as an appendix.

XBee (Digi International)

A radio module that can be connected to an Arduino through specific XBee shields. 
Pros: Easy to set-up, requires just a few lines of code. Stable communication. Arduino shield makes it easy to integrate.
Cons: Expensive (£300 SEK excluding the shield). Large and heavy (considering the Arduino Uno plus XBee shield that are required) making it less attractive for wearables.
Bluetooth with BlueSMiRF modem (Spark Fun)

A Bluetooth powered wireless serial cable replacement. Can be soldered to Arduino Pro Mini (109 SEK).
Pros: Small and light. Bluetooth (in theory) allows for one-to-many communication.
Cons: Expensive (~350 SEK). One-to-many is not set-up as standard so needs custom configuration, which might be tricky.

Bluetooth with Blend Micro (RedBearLabs)

Combined Arduino Micro and Bluetooth 4.0 Low Energy (BLE) on one board.
Pros: Extremely small and light since no external micro controller is needed.
Cons: Cheaper than BlueSMiRF but still quite expensive (~220 SEK). One-to-many is not set-up as standard so needs custom configuration, which might be tricky.

Radio frequency transmitter/receiver

A set of two small modules to communicate over radio frequency on 434MHz.
Pros: Cheap (~80 SEK per unit but only $3.95 on Spark Fun). Light and small.
Cons: Not secure, possibly unstable (Microwave might set them off). Normally used for one-to-one communication, multiple units will interfere with each other unless you code a way around it. More research is needed to consider this as a viable option.

Infrared

Invisible radiant energy, electromagnetic radiation with longer wavelengths than those of visible light.
Pros: Dirt cheap (~10 SEK). Small and light.
Cons: Requires a line of sight to communicate although because infrared bounces it can be done without a direct line of sight with a stronger signal.

Hack into consumer electronics

For example remote-controlled wall sockets.
Pros: ON/OFF communication is already set up.
Cons: Prices vary. Might be difficult the disassemble.
WIRELESS SOLUTION

After further exploring the options for wireless communication, the conclusion is that it will be too expensive no matter which option. Especially considering a minimum of 4 Arduino boards (preferably Micro or Pro Mini for best wearability) that are needed to process the wireless signals. The decision is therefore made, to aim for a partly wireless solution. Compromising between wearability and affordability. A wireless connection between the chest- (sensing) and waist- (actuating) module is made using a 433MHz radio frequency transmitter and receiver. Furthermore, the chest module will run on a Blend Micro board which can be accessed through a smartphone via a Bluetooth connection, allowing quick changes to, for example, the tilt sensitivity as well as reading out the accelerometer data.

FUNCTIONALITY

The second prototype is made smaller, lighter and partly wireless through radio frequency communication between the chest- and waist module. The three vibration motors are still connected to the waist module through wires. Vibration feedback for forward postural flexion is added, backward flexion is unnecessary because this is not considered to be an issue. The new electronics and casings (see fig. 21) are small and light enough to be placed to the body with small clips attached to the clothing. Calibration time is cut down to 3 seconds after start-up and the tiny reset button is replaced by a slide switch to re-calibrate and is moved to the chest module on the front of the body to be easily reached by the patient.

![Figure 21: The soldered electronics tightly fitting in the casings.](image-url)
TECHNICAL COMPONENTS

Chest module:
1 Arduino 'Pro Mini' 3.3V
1 ADXL337 accelerometer ±3g
1 434MHz radio frequency transmitter
4 3V coin cell batteries

Waist module:
1 Arduino 'Pro Mini' 5V
1 434MHz radio frequency receiver
1 9V battery
3 Mini vibration motors

TROUBLESHOOTING

The chest module is running on a 3.3V micro processor. As it turned out, the radio frequency modules are able to run on 3.3V but the signal strength is too low. A solution is found in adding another 2x3V coin cell battery stack, delivering 6V, and connecting it straight to the transmitter. The downside is that a little more weight and volume are added.

2.6 Validating & Evaluating II

EXPERT VALIDATION: NEURO REHAB

Neuro Rehab is a private care facility run by Eva Bramell-Risberg and Cecilia Winberg who are qualified physiotherapists with extensive clinical experience in both geriatric and neurological rehabilitation in the public and private care. Both of them are physiotherapy specialist in the field of neurology and rehabilitation training. Eva also has specialist expertise in the field of gerontology and geriatrics. The developed concept is discussed with the help of the prototype and 3D printed models to get an idea of the size and scale. Future directions for the project also came to the table. The following points are the most important outcomes of the discussion.

To start, it is important to realize the uniqueness of each patient of Parkinson's Disease. There are different symptoms and different degrees of severity for each symptom. Additionally,
there are differences in the cognitive abilities for each patient. In other words, what may work for patient A may be useless for patient B.

If we look at the problem of postural instability, the tilting is not always the first problem that occurs. What they often see at Neuro Rehab is that the muscles are affected on one side of the body. Let’s take the legs for example. When it becomes difficult to support the body on the affected leg, the stronger leg tries to compensate. This is sometimes what causes the postural instability and thus what they as physiotherapists steer on is equal distribution of weight on both legs. What can be the cause of the problem is a constant slight flexion of the knee, even when the leg is supposed to bear weight. The patient is in this case unaware of this flexion and therefore is unable to do anything about it. Compensation strategies often go unnoticed over time, until the physiotherapist shows them in front of a mirror how they are walking tilted. Correcting this is difficult and takes time. The patients ‘inner proprioceptive map’ is askew – what feels neutral is actually tilted, what is actually neutral feels tilted. Intensive physiotherapy, where the patient’s posture is constantly corrected and home exercises offer a positive result. However, if a smart wearable could be correcting the posture in the period in between therapy sessions (which is the vast majority) that might have a great positive impact on the rehabilitation process.

The concept, therefore, is deemed feasible and definitely interesting. This could be particularly helpful for patients early on the disease, who are still cognitively intact and able to actuate on postural feedback. However, it is not to be expected that this concept will eliminate the problems altogether, but achieving significant results in delaying the severity of the symptoms is not unthinkable at all. Maintaining a high quality of life for as long as possible.

They see the concept as a possible exercise tool that they would have on their shelf and which they can present to a patient they see fit for exercising outside the sessions. Probably not all day but for several hours, when walking or performing specific exercises.

Moving over to the topic of gait coaching, a possible extension point for this concept, targeted at the problems of freezing and shuffling gait. Also for this problem, the origin is not always the same for every patient. For example, cognitive issues may cause a patient to freeze when approaching a narrow hallway, because the patient is not able to process that information correctly (i.e. it is still wide enough to walk through). Furthermore, queueing methods are very diverse and personal. Sound works well for some, counting for others. Another interesting example is a woman who loved gardening but became unable to walk the narrow pathways connecting the gardens. Her solution was to lay down a rope ladder, creating a visual queue to step in one square after the other. It worked perfect for her but might be useless for another. In other words, using the vibration as queues for gait coaching is an interesting, discrete and viable option for some, but will not offer a solution for everyone.
Finally, the possibilities for collecting movement data for personal insights and statistics, as well as research purposes is considered very interesting. Next to it being a great possibility to improve communication on activities and progression, between patient and therapist, even over distance, it possibly holds great value in terms of medication. The medication for PD can be very effective but the biggest issue is that at some point the maximum dosage is reached and the medication can no longer be of help. Fine tuning the dosage, therefore, is important to spread its effect over a long a time as possible. Quantified data can be a proven way to analyze and evaluate the effect of medication on the patient, which then can be fine tuned based on facts rather than subjective reasoning.

**USER TESTING: ABELS REHAB**

In the second session at Abels Rehab with physiotherapists Erik and Malin, it was arranged that a patient that would probably benefit from the system and was willing to try it out, would join us for a user test. A slight set-back was that the developed prototype stopped functioning on the day of the user test. Efforts to find and fix the issue before the meeting were fruitless. That being said, the prototype was not essential to gather all important information but would have been the easiest tool to experience the concept first hand. Nonetheless, having the small sized electronics, the designed casings and different straps available was valuable to start a fruitful discussion. Manually turning the vibration motor on and off with an external battery allowed for feeling the strength and sensitivity of the vibrations on different parts of the body, and various contexts were imagined and discussed. These are the most interesting outcomes:

The patient has been officially diagnosed with Parkinson's Disease approximately 3 years ago but some problems already occurred before that. One of his problems is freezing, especially at night when he gets out of bed to go to the toilet. What offers a solution for him is to count (“1, 2, 3…”) or when is wife counts for him. Another problem for him is forward flexion (as an early stage of Camptocormia) when walking. Sometimes he is able to notice at, and adjust it himself. Other times, his wife corrects him on his posture when they walk together. However, when he forgets about it his posture grows worse over the time of his walk, until he eventually is bent over so much that people on the street look or stare at him. This is particularly hurting him as he doesn't want to be seen as sick or invalid but at this point the muscles in his back have grown to tired to lift the upper body back up again. For this reason, he sees great value in the concept.

When asked to think of alternative solutions he mentions some sort of corset he tried, but it was very uncomfortable and the physiotherapists also warn that a corset allows for the core muscles to weaken even further. The patient appreciates it when a device is only giving him
feedback but he himself is still in control of improving his posture. In terms of possibilities of impulses, he considers vibrations to be the best as sound in the ear would block out sounds from his environment (e.g. nature, traffic, his companions) and sound in a speaker could be confusing with all the others sounds that are already around him. Visual impulses would demand too much of his attention and would also attract his attention from others. The discreteness of vibration is a quality he is very happy with.

In terms of the proposed aesthetics, the patient didn't care much about the look but was happy with the way it looked. He was particularly impressed by the small size and weight of the modules, as it enabled him to easily carry it underneath his clothes.

Finally, the conversation reached the topic of personal statistics and insights on the smartphone. He personally owned a regular cellular phone but would be very interested to see his own performance and improvements. Although he is already performing all his physiotherapeutic exercises with great care and effort, he thinks having this information would be an extra motivation. The imagined alternative of receiving a personal update once a day in the form of a text message on this regular phone, is much appreciated. As far as the therapists could judge, not a whole lot of people with Parkinson's Disease that they treat possess a smartphone.
Looking back at the previous prototype, great improvements have been made in all three areas of design, technology and functionality, as it was the aim, further described in the previous evaluation. The second round of validation provided more grounding for the concept and again a deeper understanding of the pathology and its complexity. Experimenting and discussing the prototype with an actual patient was very valuable in the sense that it gave insights from the patient perspective, what is important for them and how do they feel about the offered and imagined solutions. However, it is important to stress that one patient does not speak for all of them and one short test session does not provide any hard evidence of significant positive effects of the system. By saying that, it is clear what needs to happen next:

The prototype will have to be made in such a way that it can endure severe and long stand-alone testing sessions. Think about the strength of the casing (i.e. being able to withstand some external impact without falling apart) and improving the wearability by minimizing the size and weight while also looking at a better way to fasten it securely. But also functional aspects as battery life and controlling the sensitivity without adding additional knobs and switches or manually reprogramming the micro controller. Once the prototype is stable enough and ready for testing, it will be interesting to try it out with different and diverse patients in the clinical environment as well as real-life contexts but with this will be something for after this thesis due to time constraints and the limited availability of patients through the collaborative partners.
2.7 Prototyping III

DESIGN

The 3D models are further improved by optimizing volume, weight and structure strength within the boundaries of the desired design aesthetic and the size of the electronics that it has to hold. The new casings are printed in the same material but with the Ultimaker 2, which is a little more accurate and has a heated print bed to assure a strong foundation of the 3D print.

In addition, two base plates are designed for the modules to encapsulate the electronics (see fig. 23). They feature a slit for the fastening mechanism and cut outs for the on/off switch and external wiring towards the vibration motors. Different color combinations are examined (e.g. black and orange gave an action sports vibe). Specific colors are selected to communicate the desired jewelry aesthetic. Black for the top and gold for the bottom and detailing.

Clips for fastening the module to the clothing are cut from thin sheet metal creating a simple, lightweight and easy to use solution that fits the elegant design (see fig. 24).
The Arduino Pro Mini board is replaced by a RedBearLab Blend Micro board, combining the functionality of the Arduino Micro and a Bluetooth communication chip. This will allow for a connection with the smartphone to set sensitivity and read-out movement data wirelessly during user testing, making the prototype smaller, lighter and thus improving wearability, also by removing the movement limitations of a wired connection. Overall delivering a more life-like situation in which the validation of the concept is most accurate.

**Figure 23:** The 3D models of the base plates for the waist (l) and chest (r) module casings.
A few small improvements have been made. The final prototype is small and light enough to be worn comfortably and (almost) invisibly but also approaches the elegance of jewelry or fashionable high-tech wearables that makes it into something you can wear with pride. The vibrations give discrete but clear feedback on the posture and the timing has been improved with a 7-second cool-down period before alerting the users on their posture, allowing the user, for example, to reach over to grab something or tilt over to kiss a loved one without letting false vibrations disturb the moment.

In the next and final chapter, the final concept and vision are elaborated and evaluated in conclusion, discussion and recommendations.
Figure 25: Final prototype, chest module.
Figure 26: Final prototype, waist module.
3. Results

3.1 Conclusion

For the conclusion, let's first return to the research question:

How could proprioceptive wearable technology assist in improving the quality of life for patients of Parkinson's Disease?

Postural instability and balance problems form one of the four main motor symptoms associated with Parkinson's Disease and it is concluded to be the symptom that most affects the quality of life in PD. It is linked to an increased risk of falling, immobility, hospitalization and the need for long-term care. Various studies indicate a proprioceptive deficit found in patients of PD to be a major factor in the cause of these issues and that patients show difficulty performing movements relying on proprioceptive integration, which include many day-to-day tasks and activities.

The answer then, is found in wearable technology, designed to be worn comfortably during these activities and interacts with the patient to offer a solution that can fill the proprioceptive gap. But increasing the quality of life goes beyond measurable statistics and assisting medical complications, how you look and feel are possibly of greater importance in your own perception of quality of life.

A final concept, as an answer on the research question or the articulation of the preferred state, was developed through an iterative design process with a focus on making functional prototypes and validation with experts. It is an intelligent lightweight wearable system consisting of one sensing module that monitors upper body posture and three actuating modules that enable discrete vibro-tactile feedback on the posture and guidance in improving it. The sensing module is worn at chest height and can be attached to most (under)garments with a small clip. Alternatively, a chest-band can be worn if preferred. The actuating modules are placed strategically on sensitive areas of the muscle groups that are responsible for correcting the posture, namely the lower back (attached with a clip to the belt, pants or skirt) for correcting forward flexion and the left and right knee pit (attached with a knee-strap) for correcting the opposite lateral flexion.

With a short 3-second calibration, the user's desired posture is established. When the desired posture is left, in either forward-, lateral flexion or both, a cool-down period of 7 seconds will start before alerting the user and guiding him or her back to the correct position through the
vibro-tactile feedback system. The thresholds (or 'sensitivity') of the posture monitor as well as the cool-down period can be changed through any smart device with a bluetooth connection, either by the patients themselves or with the guidance of their healthcare professionals.

In use, how society perceives us is important for almost every human being. Nobody wants to be viewed as weak, incapable or invalid. This is no different for patients of PD. There are a lot of medical products and systems, that can be obtrusive and communicate a strong medical vibe, attracting attention to the users impairments. This concept's design, inspired by gemstones and jewelry, tries to achieve an aesthetic that is modern, 'cool' and communicates a healthy active lifestyle similar to many wearable health gadgets out there today. The user shall be able to wear it with pride while it can also be worn (almost) invisibly, partially underneath the clothing of the user.

In effect, when applied to patients in one of the earlier stages of the disease, the proposed system could possibly be used as a preventive measure against Camptocormia and Pisa Syndrome (chronic frontal- and lateral flexion respectively) by repeatedly coaching the patient into the correct posture, avoiding spinal deformation and muscle damage due to chronic misalignments otherwise increasing in severity. Additionally, the system will make the user more self-secure and confident about its posture and in effect encourages an active and social lifestyle which is both beneficial for the health as the perceived quality of life. However, long-term studies on these effects of the system are necessary to truly validate this.

### 3.2 Discussion

The presented concept is novel and relevant in the context of Parkinson's Disease, where most value is expected at the early stages of the disease but as already mentioned in the conclusion, different elements of the concept will benefit from more extensive user testing with patients. Although of the decisions made, are firmly grounded in theory or expert validations, it is not until you put them in to practice that you can make conclusions on the performance in every-day life. However, within the limitations of this 9-week thesis project, putting the concept into practice was done at the best of my abilities.

One element that deserves a closer look in the next iteration is the vibrational impulse. The exact placement, intensity and frequency of the vibration is something that can be improved when experienced over a longer period of time. It will be extra important to involve patients with the testing of this because the mechanical threshold (i.e. at what force you feel touch) of their skin is found to be higher.
Related to this is the application of the actuating modules on the knee pits, that are, in this concept, held in place with knee straps. Possibly interesting alternative would be to have the technology small enough to be integrated in an adhesive that can be pasted directly on to the skin.

An important consideration is, that people in general do not want to be seen as sick, weak, handicapped or incapable. And neither should they have to nowadays. Look for example how optical eyeglasses transformed from medical accessory to fashion accessory. The aim then, is to make a medical accessory look cool and desirable. More a high-tech wearable than something that showcases your disabilities. Maybe eventually, it can be something you wear with pride, like a piece of jewelry.

Within Parkinson’s Disease, it will also be interesting to look into how this concept could hold value for other challenges that are faced. One aspect in this will be using the system to collect data on the patients performance and 1) use this for personal insights, visualizing performance and motivation, 2) use this evidence to communicate with the team of care specialists, for example to fine tune the dosage of different medicines and evaluate whether the effects are desired, and finally 3) when the system is used by many, the collected (anonymized) data could hold a lot of value for research purposes.

Another possible extension is on the front of gait coaching. The freezing of gait (sudden inability to move the feet and legs) is one of the other Parkinsonisms and a real problem for many patients. Different queueing strategies exist of audio or visual queues to reinstigate movement but vibration could be an interesting alternative, worthwhile pursuing in a different project. Within this concept, the vibration motors are already placed on each of the legs and the postural sensor could also measure steps. A first experiment could be to alternate vibration between left and right leg after each step is made, in such a way that the vibrating leg is the one that should move next. A step further would be to place the vibration motors underneath each foot (in the inner arch, because of the sensitivity of that area it is very ‘ticklish’ and lifting up that foot is a natural response) and vibrate until the foot is lifted and moved beyond the other foot, then we the foot is placed, the other foot starts vibrating.

Finally, with the older aged patient especially, the increased risk of falling is a real issue as it often leads to bone fractures, hospitalization and immobility. In result, some patients decide to not leave the house, but this immobility leads to more health related problems as well as a faster progression of the disease. The fear of falling works paralyzing. Possibly, the developed concept can help win the confidence back in these people, but eliminating falling entirely is unfortunately impossible. Where the concept then can lend a hand, is in fall-detection, by warning and calling a friend, family member or healthcare professional and arranging voice communication with the patient over speaker phone.
Outside of Parkinson's Disease, the system or elements thereof could hold value for other pathologies (e.g. stroke rehabilitation) as well as sports. In ballet, for example, certain movements are practiced endlessly in front of mirrors where the focus is on keeping the hips parallel to the ground. But when rehearsing the performance, a direct line of sight to a mirror is often not an option. Similarly, in swimming the proprioception plays an important role in the positioning of the body in the water as well as placement of the hand and forearm with regards to the surface in the pull- and push phase of the stroke, all while the head is facing down to the bottom of the pool.

Possibilities are endless.
ARDUINO CODE FOR CHEST MODULE

#include <VirtualWire.h>

const int numReadings = 20;
const int ledPin = 13;  // the number of the LED pin
int potPin = 3;

int readings[numReadings];  // the readings from the analog input
int index = 0;               // the index of the current reading
int total = 0;               // the running total
int averageX = 0;             // the average of X
int averageY = 0;             // the average of Y

int xpin = A3;               // x-axis or forwards postural flexion
int ypin = A2;               // y-axis or sideways postural flexion

int i;                      // loop counters

int sensorValueX;           // raw sensor values
int sensorValueY;

float smoothedValueX;       // smoothed sensor values
float smoothedValueY;

float calibratedValueX;     // calibrated sensor values
float calibratedValueY;

float filterVal;            // this determines smoothness - .0001 is max 1 is off (no smoothing)

int x_minCal = 1023;         // calibrated parameters
int x_maxCal = 0;
int y_minCal = 1023;
int y_maxCal = 0;
char *controller;

void setup() {
  Serial.begin(115200);

  for (int thisReading = 0; thisReading < numReadings; thisReading++)
  readings[thisReading] = 0;

  pinMode(ledPin, OUTPUT);
  pinMode(potPin, INPUT);

  // turn on LED to signal the start of the calibration period:
  digitalWrite(ledPin, HIGH);

  // calibrate during the first three seconds
  while (millis() < 3000) {
    sensorValueX = analogRead(xpin);
    filterVal = 0.1;
    calibratedValueX = smoothX(sensorValueX, filterVal, calibratedValueX);

    // record the maximum sensor value
    if (calibratedValueX > x_maxCal) {
      x_maxCal = calibratedValueX;
    }

    // record the minimum sensor value
    if (calibratedValueX < x_minCal) {
      x_minCal = calibratedValueX;
    }

    sensorValueY = analogRead(ypin);
    calibratedValueY = smoothY(sensorValueY, filterVal, calibratedValueY);
  }
}
// record the maximum sensor value
if (calibratedValueY > y_maxCal) {
    y_maxCal = calibratedValueY;
}

// record the minimum sensor value
if (calibratedValueY < y_minCal) {
    y_minCal = calibratedValueY;
}

// signal the end of the calibration period
digitalWrite(ledPin, LOW);

vw_set_ptt_inverted(true); //
vw_set_tX_pin(12);
vw_setup(200); // speed of data transfer Kbps
}

void loop(){

    // read the potmeter for sensitivity
    int potValue = digitalRead(3);
    int scaledPot = 0; // map(potValue, 0, 1023, 0, 20);
    int x_max = x_maxCal + scaledPot;
    int x_min = x_minCal - scaledPot;
    int y_max = y_maxCal + scaledPot;
    int y_min = y_minCal + 48 - scaledPot; // +48 to adjust for consistent insensitivity on the y_min side.

    filterVal = 0.01;

    sensorValueX = analogRead(xpin);
    sensorValueY = analogRead(ypin);

    smoothedValueX = smoothX(sensorValueX, filterVal, smoothedValueX);
    smoothedValueY = smoothY(sensorValueY, filterVal, smoothedValueY);

    int scaledPot = 0;
    Serial.print(scaledPot);
    Serial.print("          ");
    Serial.print(x_max);
    Serial.print("      ");
    Serial.print(smoothedValueX);
    Serial.print("          ");
    Serial.print(y_min);
    Serial.print("   ");
    Serial.print(y_max);
    Serial.print("      ");
    Serial.println(smoothedValueY);

    if (smoothedValueX > x_max && smoothedValueY <= y_max && smoothedValueY >= y_min) { // forward tilt
        Serial.println("forward");
        // send high signal:
        controller="w";
        vw_send((uint8_t *)controller, strlen(controller));
        vw_wait_tX(); // Wait until the whole message is gone
digitalWrite(ledPin, HIGH);
delay(50);
    }

    if (smoothedValueY > y_max && smoothedValueX <= x_max) { // left tilt
        Serial.println("left");
        // send high signal:
        controller="a";
        vw_send((uint8_t *)controller, strlen(controller));
        vw_wait_tX(); // Wait until the whole message is gone
digitalWrite(ledPin, HIGH);
delay(50);
    }

    if (smoothedValueY < y_min && smoothedValueX <= x_max) { // right tilt
        Serial.println("right");
        // send high signal:
        controller="d";
        vw_send((uint8_t *)controller, strlen(controller));
        vw_wait_tX(); // Wait until the whole message is gone
digitalWrite(ledPin, HIGH);
    }

delay(50);

if (smoothedValueY < y_min && smoothedValueX > x_max) { // right+forward tilt
    Serial.println("right+forward");
    // send low signal:
    controller="e";
    vw_send((uint8_t *)controller, strlen(controller));
    vw_wait_tx(); // Wait until the whole message is gone
    Serial.println("neutral");
    digitalWrite(ledPin, HIGH);
    delay(50);
}

if (smoothedValueY > y_max && smoothedValueX > x_max) { // left+forward tilt
    Serial.println("left+forward");
    // send low signal:
    controller="q";
    vw_send((uint8_t *)controller, strlen(controller));
    vw_wait_tx(); // Wait until the whole message is gone
    Serial.println("neutral");
    digitalWrite(ledPin, HIGH);
    delay(50);
}

if (smoothedValueY >= y_min && smoothedValueY <= y_max && smoothedValueX <= x_max) { // neutral posture
    Serial.println("neutral");
    // send low signal:
    controller="s";
    vw_send((uint8_t *)controller, strlen(controller));
    vw_wait_tx(); // Wait until the whole message is gone
    Serial.println("neutral");
    digitalWrite(ledPin, LOW);
    delay(50);
}

// smooth rules

int smoothX(int data, float filterVal, float smoothedValueX){
    if (filterVal > 1) { // check to make sure param's are within range
        filterVal = .99;
    } else if (filterVal <= 0) {
        filterVal = 0;
    }
    smoothedValueX = (data * (1 - filterVal)) + (smoothedValueX * filterVal);
    return (int)smoothedValueX;
}

int smoothY(int data, float filterVal, float smoothedValueY){
    if (filterVal > 1) { // check to make sure param's are within range
        filterVal = .99;
    } else if (filterVal <= 0) {
        filterVal = 0;
    }
    smoothedValueY = (data * (1 - filterVal)) + (smoothedValueY * filterVal);
    return (int)smoothedValueY;
}

#include <VirtualWire.h>

const int ledPin = 13; // the number of the LED pin
const int fwdPin = 3; // the number of the LED pin
const int lftPin = 5; // the number of the LED pin
const int rgtPin = 6; // the number of the LED pin
void setup()
{

}
vw_set_ptt_inverted(true); // Required for DR3100
vw_set_rx_pin(12);
vw_setup(200); // Bits per sec
pinMode(fwdPin, OUTPUT);
pinMode(lftPin, OUTPUT);
pinMode(rgtPin, OUTPUT);
pinMode(ledPin, OUTPUT);

vw_rx_start(); // Start the receiver PLL running
}

void loop() {
  uint8_t buf[VW_MAX_MESSAGE_LEN];
  uint8_t buflen = VW_MAX_MESSAGE_LEN;

  if (vw_get_message(buf, &buflen)) // Non-blocking
  {
    if(buf[0] == 's') { // neutral
      digitalWrite(fwdPin, LOW);
      digitalWrite(lftPin, LOW);
      digitalWrite(rgtPin, LOW);
      digitalWrite(ledPin, LOW);
    }
    else if(buf[0] == 'a') { // left
      digitalWrite(fwdPin, LOW);
      digitalWrite(lftPin, HIGH);
      digitalWrite(rgtPin, LOW);
      digitalWrite(ledPin, HIGH);
    }
    else if(buf[0] == 'w') { // forward
      digitalWrite(fwdPin, HIGH);
      digitalWrite(lftPin, LOW);
      digitalWrite(rgtPin, LOW);
      digitalWrite(ledPin, HIGH);
    }
    else if(buf[0] == 'd') { // right
      digitalWrite(fwdPin, LOW);
      digitalWrite(lftPin, LOW);
      digitalWrite(rgtPin, HIGH);
      digitalWrite(ledPin, HIGH);
    }
    else if(buf[0] == 'q') { // forward-left
      digitalWrite(fwdPin, HIGH);
      digitalWrite(lftPin, HIGH);
      digitalWrite(rgtPin, LOW);
      digitalWrite(ledPin, HIGH);
    }
    else if(buf[0] == 'e') { // forward-right
      digitalWrite(fwdPin, HIGH);
      digitalWrite(lftPin, LOW);
      digitalWrite(rgtPin, HIGH);
      digitalWrite(ledPin, HIGH);
    }
  }
}
References


IDEO Method Cards: 51 ways to inspire design; learn, look, ask, try. (2003). London: IDEO.


Images


Primary Stabilizing Muscles for during Anterior/Posterior Postural Sway [Online image]. Retrieved April 29, 2015 from http://media.lanecce.edu/