Pontifícia Universidade Católica do Rio de Janeiro

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StableBelt:

Wearables in Core Stabilization

Dissertação de Mestrado

Dissertation presented to the Programa de Pós-Graduação em Informática of the Departamento de Informática, PUC-Rio as partial fulfillment of the requirements for the degree of Mestre em Informática.

Advisor: Prof. Hugo Fuks

Rio de Janeiro

March 2016

PONTIFÍCIA UNIVERSIDADE CATÓLICA
DO RIO DE JANEIRO

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Bibliographic data

Ismério, Fernando Cardoso

StableBelt: Wearables in Core Stabilization / Fernando Cardoso Ismério ; advisor: Hugo Fuks. – 2016.

130 f. : il. (color.) ; 30 cm

Dissertação (mestrado)–Pontifícia Universidade Católica do Rio de Janeiro, Departamento de Informática, 2016.

Inclui bibliografia.

1. Informática – Teses. 2. Tecnologia Vestível. 3. ÁudioFeedback. 4. Reabilitação. 5. Lombalgia. 6. Computação ubíqua. I. Fuks, Hugo. II. Pontifícia Universidade Católica do Rio de Janeiro. Departamento de Informática. III. Título.

CDD: 004

To those who may benefit from this work.

Acknowledgements

First and foremost, I thank God, for the countless opportunities of new beginnings.

I thank my family for the constant support through the challenges that were encountered during this journey. Specially, my mother whose patience has no bounds.

I would like to thank my advisor Prof. Hugo Fuks for his directions, comments, suggestions, continuous support and immense knowledge and time sharing.

I express my sincere gratitude to the research participants without whom this work would not have been possible and whose names are preserved in respect to their privacy and to the research protocol: thank you for your valuable time, for your cooperation and for teaching me much more than I can write here.

I thank the colleagues from SecondLab, for their friendship, patience, insights and discussions over the course of this research: Marcio, Bruno Chagas, Bruno Pontes, Wallace, Katia. Marcio Cunha and Bruno Chagas, for technical consulting. My colleagues from Data Sciences: Cassio Almeida e Sonia Fiol, for their generosity and support generating graphs. The physical therapists that provided essential information during interviews: Prof. Felipe Reis, Edmur Paranhos, Denise Tenius, Valeria Rosa Pinto, Lilian Ponzoni, Prof. Paulo Ferreira. The designers from the Design Workshop at the Museum of Art, Rio de Janeiro (MAR).

I would also like to thank all the professors, friends and colleagues from PUC-Rio graduate program whose names would be too many to mention here, with whom I shared classes, study hours or just coffees, enough to make me admire them all.

Finally, I thank PUC-Rio and CNPq for the partial financial support.

Abstract

Ismério, Fernando Cardoso; Fuks, Hugo (Advisor). **StableBelt: Wearables in Core Stabilization**. Rio de Janeiro, 2016. 130p. MSc. Dissertation – Departamento de Informática, Pontifícia Universidade Católica do Rio de Janeiro.

In this dissertation, different types of audio biofeedback (ABF) for core stabilization exercises using motion sensors are investigated. Core stabilization exercises are one of the strategies used in the treatment of low back pain. The Supine Bridge (SB) exercise was chosen as the focus for the investigation. The primary motion sensor used was a tri-axial accelerometer. Flex Sensors, Force Sensitive Resistors and multiple accelerometers were also used in other prototypes. The results of this dissertation, which include data from accelerometer, comments, process, reflections, and implementation of prototypes that generate 3 types of audio biofeedback, were gathered during 5 cycles of action research. In action research, the researcher conducts the research performing successive actions that attempt to reduce a specific problem in a real world environment. In this dissertation, the environment chosen was a place where a patient executes exercises and the problem identified is the difficulty of the patient to perform the exercises correctly. The action was the introduction of a wearable – StableBelt – which generates audio biofeedback based on the patient's movements during a core stabilization exercise. Different types of audio were investigated: instrumental music, piano and drums. The StableBelt was evaluated through 3 user tests. After a preliminary test with one participant, user tests with 5 and 8 participants were conducted. In the preliminary test, instrumental music was used and piano and drums in later tests. The last cycle of the action research was dedicated to the comfort of the StableBelt. During the investigation, physical therapists which research low back pain and physical therapists which use core stabilization exercises in their clinical practice were interviewed.

Keywords

Wearable Computing; Rehabilitation; Low Back Pain; Ubiquitous Computing.

Resumo

Ismério, Fernando Cardoso Fuks, Hugo (Orientador). **StableBelt: Wearables em Estabilização Segmentar.** Rio de Janeiro, 2016. 130p. Dissertação de Mestrado – Departamento de Informática, Pontifícia Universidade Católica do Rio de Janeiro.

Nesta dissertação são investigadas formas de áudio biofeedback (ABF) para exercícios de estabilização segmentar usando sensores de movimento. A estabilização segmentar é uma das estratégias no tratamento de lombalgias. O exercício de Ponte foi escolhido como foco para a investigação. O sensor de movimento principal foi um acelerômetro tri-axial. Flex Sensors, Force Sensitive Resistor e múltiplos acelerômetros foram usados em outros protótipos. Os resultados desta dissertação, que incluem dados do acelerômetro, comentários, procedimentos, reflexões e implementação de protótipos com geração de 3 tipos de ABF, foram obtidos durante 5 ciclos de uma pesquisa-ação. Na pesquisa-ação, o pesquisador conduz a pesquisa realizando ações sucessivas que busquem reduzir um problema específico em um ambiente real. Nesta dissertação, o ambiente usado foi um local onde um paciente executa exercícios de estabilização segmentar e o problema identificado é a dificuldade do paciente executar os exercícios de forma correta. A ação é a disponibilização de um wearable – StableBelt – que produz ABF baseado nos movimentos do paciente durante um exercício de estabilização segmentar. Diferentes formas de áudio foram investigadas: música instrumental, piano e percussão. O StableBelt foi avaliado através de 3 testes com usuários. Após um teste preliminar com um participante, testes com 5 e depois 8 participantes foram feitos. No teste preliminar foi usada música instrumental e piano e percussão nos testes subsequentes. O último ciclo da pesquisa-ação foi dedicado ao conforto do StableBelt. Durante a investigação, foram entrevistados fisioterapeutas que pesquisam lombalgia e fisioterapeutas que usam estabilização segmentar na clínica.

Palavras-chave

Tecnologia vestivel; Reabilitação; Lombalgia; Computação Ubíqua.

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1
Introduction

This dissertation is an investigation of how wearables can be applied to core stabilization exercises. The objective of the investigation is to gain preliminary understanding of how audio biofeedback (ABF) affects the execution of the Supine Bridge (SB) exercise. My primary contribution is a set of design suggestions for ABF to be used in core stabilization exercises. The audio biofeedback, in this research, is based on data gathered by an accelerometer, which is a component of a wearable – StableBelt.

I am a physical therapist and a computer scientist researching in the area of Internet of Things and Wearables. While investigating potential uses of motion sensors for rehabilitation, I identified an opportunity for using these sensors to provide audio biofeedback to core stabilization exercises used in the treatment of low back pain. Further, since much of the feedback provided for exercises is focused on visual display, it would be useful to explore feedback methods based entirely on auditory information, allowing eyes to be closed, or gaze to be free to be directed to where it is most comfortable. This could provide additional rest to the overload of visual information we attend to everyday.

Core stabilization exercises are a common strategy in the treatment of Non-Specific Low Back Pain (NSLBP), which is a condition that affects a large percentage of the world's population at some point in their lives and is a cause of much of absenteeism in the workplace (Dagenais, et al., 2008; Vassilaki & Hurwitz, 2014). Moreover, NSLBP is a widely researched topic providing a good basis for this investigation (Van Middelkoop, et al., 2011). Our research group at the SecondLab, Department of Informatics, PUC-Rio, was well positioned to investigate this problem, since it had expertise in Computer Science, Computer Engineering and Physical Therapy. With the help of my colleagues, I was able to explore different audio biofeedback alternatives to assist patients performing core stabilization exercises.

My efforts were focused on the SB exercise. This exercise consists in having a person lie down on a firm surface, with the knees bent and soles of the feet touching the surface. The person raises the hips until shoulders, hips and knees are aligned. Once the alignment position is reached, the person maintains for a period of time and then lower the hips to the initial position (Bjerkefors, et al., 2010).

Initially, the StableBelt consisted of an elastic belt with a small pocket where a plastic case containing a motion sensor was placed. This motion sensor communicated with a laptop computer, which generated the audio biofeedback. The motion sensor was a tri-axial accelerometer integrated into a microcontroller. Towards the end of my research, the elastic belt was replaced with a new design, made of neoprene that eliminated the need for the plastic case.

Related work was reviewed from two different perspectives. First, how motion sensors and biofeedback are used in posture and balance exercises. Closer to my configuration, I encountered three commercial products that claim to provide solutions to rehabilitation with inertial sensors and wearables. All three products take different strategies. The three products do not describe details of their implementation or of the exercises. Research papers related to research on these products usage have only been published recently (Costa, et al., 2013; Kent, et al., 2015; Hügli et al. 2015). The products represented in these papers have been available on the market for a few years. Additionally, as requested by the advisory committee during the defense, I reviewed papers on the perception of music and sound as it relates to feedback.

Action research was chosen as a research method because it allowed me to conduct the research performing successive actions to attempt to reduce a specific problem in a real world environment (Herr and Anderson, 2005). The focus on actions in the world, observations and reflections was aligned with the needs of my research. In this dissertation, the environment chosen was a place where a patient executes exercises and the problem identified is the difficulty of the patient to perform the exercises correctly. The action was the introduction of a wearable – StableBelt – which generates audio biofeedback based on the patient's movements during a core stabilization exercise.

My action research consisted of five cycles. The first cycle was dedicated to learning the sensor technology, the programming environment and prototyping the first StableBelt. In this cycle, the audio feedback was based on recorded instrumental acoustic guitar music. This prototype was tested with one participant.

The second cycle was intended to enhance the StableBelt with additional sensor data to be used in the Audio Biofeedback generation. I explored flex sensors and Force Sensitive Resistors (FSR). Both sensors were used in breadboard prototypes to understand their sensitivity. When explorations placed these sensors in contact with the physical body, challenges were encountered and they did not materialize in viable solutions. In addition, during the second cycle, based on knowledge gathered during interviews with two physical therapists, I decided to prototype a solution with 2 motion sensors communicating with the computer simultaneously to generate audio biofeedback. The separate motion sensors would enable core stabilization exercises that would be performed standing. Given the programming challenges encountered and the inability to estimate a completion date for the prototype with 2 motion sensors, I decided to discard this prototyping effort. Hence, no user tests were conducted during the second cycle.

In the third cycle, I resumed the single sensor strategy and focused on the type of audio being generated. In order to make the audio biofeedback more easily understood, two distinct timbres were added, based on piano and drum simulations. During this cycle, I conducted a test with 5 participants. The logs showed considerable improvement from the test in the first cycle.

The fourth cycle included an automated prototype that could be used in the context of a patient at home without supervision from a physical therapist. During the fourth cycle, I conducted a test with 8 participants. In each session, exercises were followed by a semi-structured interview. All sessions were recorded on video. This cycle produced most the data used in this research, enabling rich analysis and discussion, and producing the majority of the insights represented in this dissertation.

The fifth cycle focused on a new design for the belt. This design was started during a workshop at Museu de Arte do Rio (MAR). It was intended to address comments from previous tests regarding lack of comfort of the belt. Since the new design did not modify aspects of the audio biofeedback, I decide not to conduct a user test in this cycle.

In the next section, I cover my two primary motivations for the explorations that are described in this dissertation.

1.1 Motivation

Two aspects of this research motivated me while searching for a topic and subsequent efforts. The first motivation was to explore simple low cost solutions to assist rehabilitation patients during exercises and potentially serve as encouragement. I was interested in experimenting with an interactive environment that was much simpler than a typical computer game, containing only auditory feedback and no visual display, and perhaps provide a small fraction of the benefits of music therapy (Clair, et al., 2012), by embedding positive reinforcement in a non-verbal abstract audio feedback.

My second motivation for this investigation was to explore a topic situated in the intersection of two areas of my background: Computer Science and Physical Therapy. I received my Bachelors degree in Computer Science from University of California, Los Angeles, in 1986 and spent 13 years at IBM Corporation as software engineer, first in Quality Assurance and Software Testing (5 years) and subsequently moved to Human Factors collaborating on diverse tasks, including: prototyping, running usability tests, focus groups, and user interface design. I currently work as a researcher in the SecondLab, Department of Informatics, PUC-Rio, Brazil, a laboratory dedicated to research in Internet of Things (IoT), Assistive Technology and Wearables.

In 2010, I received my Bachelors degree in Physical Therapy from the Instituto Brasileiro de Medicina de Reabilitação. While studying Physical Therapy, I worked as an intern in clinics and hospitals, working with different modalities: Aquatic rehabilitation, Geriatrics, and Intensive Care Unit. I am a trained Pilates Instructor and received my certification from Polestar Education in Rio de Janeiro, in 2002. I worked as Pilates Instructor for 7 years and have taught the SB exercise during my classes.

Prior to arriving at the topic of this dissertation, I reviewed the literature and brainstormed on how inertial motion sensors could provide feedback during physical exercises, focusing on older adults, initially. During this effort, I became interest in audio as a modality for feedback.

During a meeting with physical therapist Edmur Paranhos (who has a private practice) on April 21, 2015, to explore potential research directions, we identified stabilization exercises as area of interest. We discussed what types of activities could benefit the most from a single motion sensor and audio feedback. We considered stabilization tasks were better suited for an initial exploration of this technology than complex movement tasks.

The following section describes how this document is organized.

1.2
Structure of this dissertation

This dissertation is organized in six chapters. After the introduction, chapter 2 covers some background topics in physical rehabilitation related to core stabilization exercises. Chapter 3 describes references to related research work. Chapter 4 discusses the method I used to conduct the research. Chapter 5 describes the five cycles that comprised the action research. Chapter 6 provides a final discussion, summarizes my conclusions and points to related future work.

2
Context

In this section, I will provide a brief overview of concepts related rehabilitation of low back pain and background on perception of music and sound to help the reader contextualize my research.

2.1
Rehabilitation of Low Back Pain

In this section, I will provide some background on the core stabilization exercises and the SB exercise in particular, highlighting some of the relevant history of the related research. Considering I am not proposing any new theories from a physical therapy research perspective, this section is intended to be a general overview of the related concepts and is not exhaustive.

2.1.1
Core Stabilization Exercises

The research that supports the core stabilization exercises, started with the spinal stability model proposed by Panjabi (1989). He conceived an intricate model for how active structures (muscles), controlled by the motor cortex (control system) in the brain, interact with passive structures (ligaments) to maintain stability (Panjabi, et al., 1989). Figure 1 shows the model in graphical form.

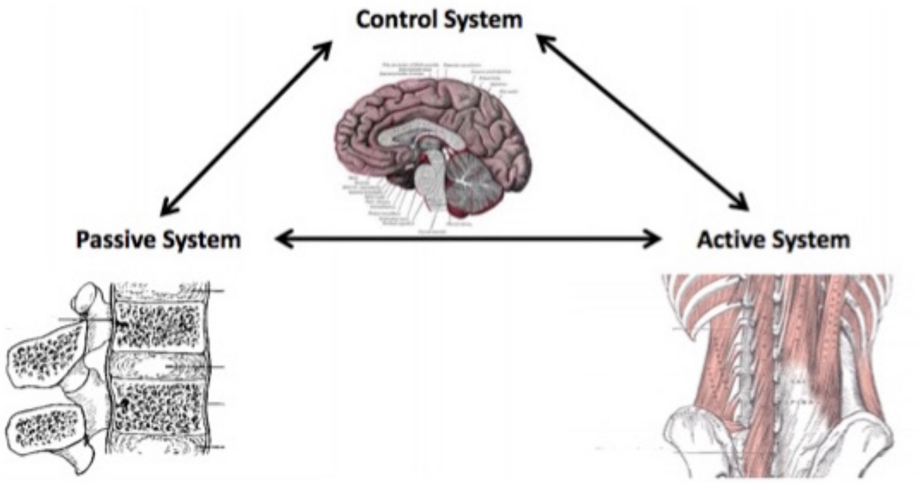


Figure 1 - The Panjabi model of spinal stability

Carolyn Richardson, Paul Hodges, Julie Hides and colleagues followed with more than a decade of detailed laboratory experiments and clinical observations (Richardson, et al., 2004). Initially, they thought Non-Specific Low Back Pain (NSLBP) came from micro-injuries that were accumulated over time and eventually led to degeneration of spinal structures, causing instability and pain. After a number of experiments, some with astronauts who spent time in low gravity environment, a new explanation involving decrease in function of anti-gravity muscles was formulated. The new understanding gradually was refined to become what are now segmental stabilization or core stabilization exercises. Figure 2 shows the three stages that comprise segmental stabilization exercise progression. Start with activation of deep, local, anti-gravitational muscles (transverse abdominis, multifidus, and pelvic floor muscles), represented by the inner circle, labeled 1 in Figure 2. Once this activation is occurring with ease, precision and no pain, the patient moves to the next stage – closed kinetic chain, slow exercises[1]. Finally, when stage 2 is mastered, the patient moves to open kinetic chain, fast exercises. Some of the exercises in stage 3 may be similar to activities that triggered the initial pain. For example, if the patient is an athlete, at this stage, he will gradually resume the movements that enable him to start to perform his sport.

[1] In closed kinetic chain, the extremity of the limb being exercised is placed against a fixed surface. For example, when doing exercises for the legs, the feet are on the ground or platform.

Figure 2 - The three stages of segmental stabilization.

The exercises, depicted in Figure 2, do not include the SB exercise explicitly. However, the characteristics of the exercises in Stage 2 – Slow, closed-kinetic chain – are the same as those of the SB exercise and it should be associated with this stage. The SB exercise should be prescribed after Stage 1 exercises have been mastered without pain.

2.1.2 The Supine Bridge Exercise

The Supine Bridge Exercise starts with a person lying down on his back with knees bent (Figure 3). The person raises his hips slowly until shoulder, hips and knees are aligned and maintains for a period of time. The person lowers the hips to the initial position. In this research, participants of our tests maintained the hips raised during 22 seconds. I chose the duration of 22 seconds, after some personal trials. This duration provided a balance between the amount of data gathered and potential for fatigue. The reason I chose 22 seconds and not 20 seconds was an initial concern that two seconds may have to be discarded to allow for initial adjustment. This proved not to be the case and I kept the 22 seconds duration for comparison purposes.

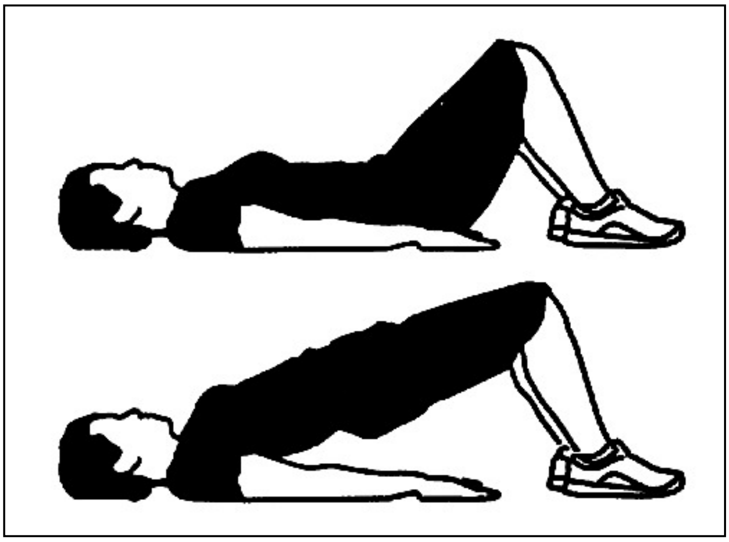


Figure 3 – The Supine Bridge exercise

The SB exercise was chosen based on its simplicity and the possibility of adequately measure stability (lack of movement) with one tri-axial accelerometer. This exercise was suggested during a conversation with Professor Felipe Reis (Hospital Gaffrée e Guinle; Instituto Federal de Educação, Ciência e Tecnologia, Rio de Janeiro) held on June 10th, 2015 at Hospital Gaffrée e Guinle. The SB exercise has been used to assess muscle contraction with EMG and hollowing commands (Bjerkefors, et al., 2010). I specify Supine Bridge exercise to distinguish from the Side Bridge, which is another exercise used in core stabilization. The Side Bridge is performed with the forearm and lower leg placed on the ground and the body positioned laterally to the ground.

Gilherme "Fiapo" Tenius, a sports physical therapist, said during informal conversation on January 9th, 2016, that when prescribing the SB, during core strengthening, he usually does not pause the movement at the apex for more than 2 or 3 seconds. He does, however, prescribe the single legged variation, a few times once the patient has raised his hips (Figure 4, B and C). The number of times increases as the patient improves strength and control.

Paulo Ferreira, a Physical Therapy professor at the University of Sidney, Faculty of Health Sciences, who does research on low back pain, wrote during email exchange on January 7th, 2016, that when he was working as a physical therapist, he guided SB exercises to be executed "slowly, with small loads, and no pause, in order *not* to recruit global muscles".

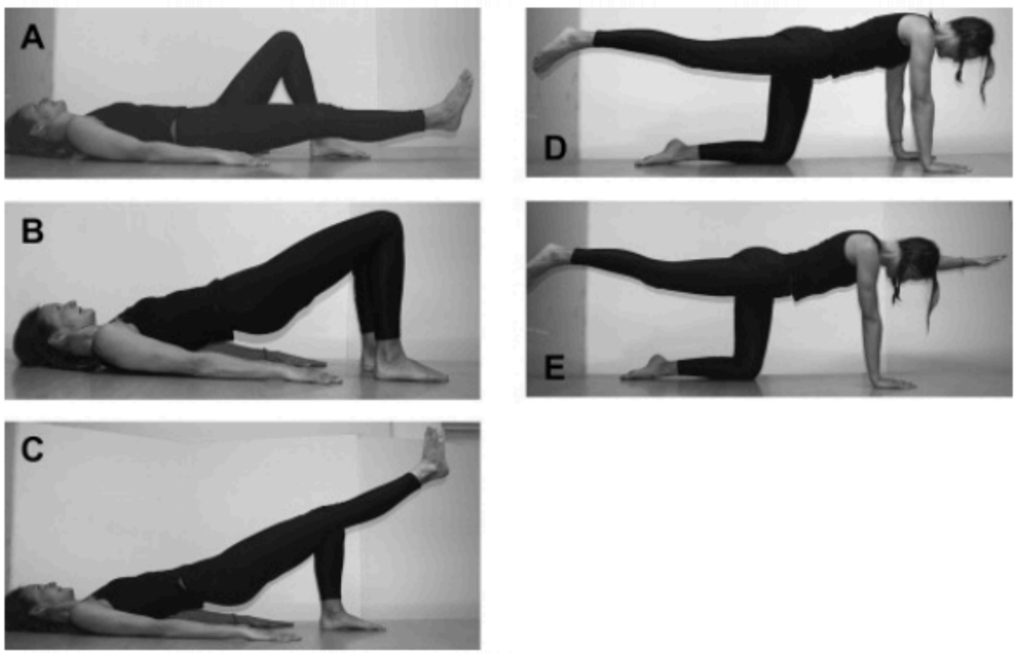


Figure 4 – Core stabilization exercises used in previous research. The Supine Bridge exercise is shown in B.

Leo Costa, a Physical Therapy professor at the Universidade Cidade de São Paulo (UNICID) wrote via email, on January 10th, 2016:

> From my perspective, there is no exact answer to this question because the decision will depend on the clinical assessment of the patient. If the patient has no ability to control, I will go until a range (of motion) in which there is control and work isometrically in this position. Later I will advance and progress according to the improvement in neuromuscular control. At the end, this task can be done 100% dynamic.
> Remember the Pirelli advertisement: "power is nothing without control" … so, only evolve to more dynamic postures, when the system has enough control for them. (Author's translation from Portuguese)

If results from using the audio biofeedback are positive for this relatively simple exercise, we may gain understanding that could be used in slightly more complex core stabilization exercises, providing some initial support for another alternative non-invasive strategy for treating NSLBP.

2.2
Perception of music and sound

The literature on perception of music and sound is vast. In this section, I will summarize my findings and point to some of the aspects of the perception of music and sound that I found most relevant to my investigation. Some of the literature referenced in this section deals specifically with aspects of perception of music and other references discuss perception of sounds in general.

Music is a pervasive aspect of life and the wide range of research areas related to how we perceive music makes finding a starting point to the study a challenge. Levitin (2011) provides a comprehensive coverage of topics in music perception (Levitin, 2011). To facilitate our understanding, he describes the most important components of music: pitch, rhythm, tempo, contour, timbre, loudness and reverberation. Together these elements combine to form higher-order concepts, such as: meter, key, melody, and harmony. Being able to hear and differentiate these components is essential to much of research on music perception. While investigating music through cognitive neuroscience, it is important to use real-world music rather than simplified abstracted sounds. However, in my research, the simplified sounds seemed to allow for faster recognition of changing values communicated by the feedback. In music perception, there is a low-level bottom-up process of feature extraction combined with a top-down process of anticipation based on context and memory. The setting up and manipulating of expectations is the heart of music and it is accomplished in countless ways. One widely researched area is the relation between music, emotion and memory. How are music memories different and why are they evocative? How does expectation in music generate emotion? There are competing theories in how music is categorized. For the listener, the basic structure needs to be understood so that liberties can be appreciated. There is constant interplay between structure and surprise. When contemplating designs for auditory warnings, one should take into account the fact that the auditory startle is the fastest and arguably most important of our startle responses. Current neuropsychological theories associate positive mood and affect with increased dopamine levels. Music is clearly a means for improving peoples moods. Is the simple Do-Re-Mi sequence repeated in my feedback enough to evoke positive affect? This sequence should create a very simple expectation. The sudden percussion sound, when user moves out of correct alignment, breaks this expectation and causes surprise.

Emotions and music is an area that has attracted attention for decades and many open questions remain. Scherer (2004) provides theoretical framework for investigating which emotions can be induced by music and how we can measure them (Scherer, 2004). Of particular interest are complex emotions that have not been adequately addressed by previous research. He is careful to detail what exactly is meant by emotion. He lists two major theoretical mechanisms of induction: Central route production, Peripheral route production.

In trying to relate emotions to specific features, Van der Zwaag (2011) investigated the influence of the musical characteristics of tempo, mode and percussiveness on emotions (Van der Zwaag, et al., 2011). According to Van der Zwaag, Valence (i.e. overall happiness) and arousal (i.e. excitement or bodily activation) are the two most important dimensions to assess emotion. Previous research showed expectancy violations within the melody of music will induce surprise and eventually increase arousal when many such expectancy violations occur (Deliège, et al., 2004). Complex, thick harmonies are appraised with low valence, whereas simple, thin harmonies are associated with high valence levels. Staccato articulated music has been found to induce more fear and anger emotions than legato articulated music, which is more often associated with tenderness or sadness (Juslin, 1997). The mostly widely studied characteristics are mode and tempo. Tempo is seen as the most important characteristic in modulating affect and can influence a range of emotional expressions: happiness, surprise, pleasantness, anger and fear. In western tonal context, musical mode is associated with valence dimension: the minor mode is associated with sadness, where music in the major mode induces happiness. Percussiveness is a less researched characteristic and is found to be associated with the impact of music. Most of the studies with music have been conducted in controlled laboratory setting. Van der Zwaag investigated music played in background with subjects performing an office task. They used pop music, which generally do not to have strong negative valence. Some of their results contradict previous research. The arousal values relative to percussiveness appear in the skin conductance levels but not in the subjectively experienced responses. This confirmed the importance of physiological responses in measuring the influence of music on emotions. Their findings support the emotivist view as opposed to the cognitivist view. Their primary findings were that fast tempo can be presented to boost arousal levels. When fast tempo or major mode is combined with high-percussion levels, a more positive valence will be evoked. Music presentation in laboratory settings can yield different responses than in more ecological valid settings. This illustrates the importance of understanding music in everyday-life settings, which include all the interacting music characteristics within real music, when aiming to understand the mechanisms by which music influences our emotions.

To understand the results from (Van der Zwaag, et al., 2011) in relation to my investigation, we need to know whether these findings hold for simple abstract sounds that can be felt as music but do not have the rich composition found in most of the music used in perception research. The primary purpose of my sounds is to convey feedback for correct position during the exercise. Which of the effects found in music research on emotions, if any, should I expect with my particular use of sounds?

In contrast to positive affects, Garrido (2011) tries to elucidate why people listen to music that evokes negative emotions (Garrido and Schubert, 2011). The arguments of the discussion around this issue can also be broadly divided into that of cognitivists and emotivists. This research focused around the motivations for seeking sad music and the cognitive mechanisms that may make it possible to enjoy the experience of negative emotions in an aesthetic context. The reasons to listen to music for these participants were: mood regulation, arousal, relaxation and calming, and distraction. Participants chose sad music with the following intentions: arousal, reflection, nostalgia, grief. While much of the time emotional arousal may be the aspect attracts, some may seek out prior mood may cause some to seek out sad music in order to experience particular psychological benefits such as reflecting on life-events, enjoying emotional communion, or engaging in a process of grieving. I suspect the simple sounds used in my research do not evoke strong negative emotions in most people, but it is certainly an aspect to be aware and consider.

Applying knowledge from research on emotions induced by music, Daly (2015) investigated affectively–driven music generation and its effects on healthy participants (Daly, et al., 2015). The music generation system was tested via listener reports and physiological measures. The material generated incorporated a range of musical features with known affective correlates: tempo, mode, pitch range, timbre, and amplitude envelope. Compositions were manipulated according to an affective mapping, which gave control over the five musical features. They observed that the music generation system was able to induce a range of targeted emotions. In their study, physiological differences between high and low valence took place in the first 2 to 8 seconds of exposure to music. Given the number of features that had to vary in different combinations, it is likely their generated music is much more complex than the sounds used in my research.

The relationship between music and our assessment of time is another area of research than could be leveraged in designing audio feedback. Kellaris (1992) experimented with temporal perceptions as influenced by music (Kellaris and Kent, 1992). They found perceived duration was longest for subjects exposed to positively valenced (major key) music, and shortest for negatively valenced (atonal) music. In other words, time did not seem shorter when an interval was filled with affectively positive stimulation. An alternative hypothesis based on attentional and retrieval process is supported. Their experiment explored modality in relation to temporal perception. Modality refers to the configuration of intervals between pitches that comprise a scale. The most common modes in western culture are the conventional major and minor keys. Whereas major keys tend to evoke generally positive feelings, minor keys are often perceived as sentimental, melancholy, or plaintive. There are also modalities that are neither major nor minor that can be classified as atonal. Atonal modalities are generally perceived as less pleasant than conventional (major and minor) modes by untrained listeners. The study suggests that music in major key might be used when longer perceived duration is desirable and minor key when shorter perceived duration is intended. In real life environments, where music may be heard but not listened to, other acoustic features may be more relevant, such as tempo or rhythm. It is possible that pace of environmental music could alter the speed of the internal clock people are presumed to use in making temporal judgments. What implications do these results have for choices regarding audio feedback? In my user tests, if the 3 notes

(1 second each) are perceived as a single chunk of time. Participants may perceive the 22 seconds of maintaining the SB position as taking less time than when only a single note is repeated every second. The stimuli of 3 notes being accounted for the same way as a single note, but in fewer numbers. The more repetitive single note may, also, seem relatively more annoying.

Our ability to quickly recognize musical patterns is another area of interest. Schulkind (2003) investigated musical features that facilitate our recognition of a particular musical composition, as in "Name that Tune" (Schulkind, et al., 2003). One interesting finding was that identification happened in a holistic, all-or-none process and that parallels can be drawn between melody and spoken word identification. They used the fact that a musical feature that is difficult to perceive will be unlikely to aid identification. The two primary questions to answer were: 1. what are the fundamental units that are used in to identify familiar melodies? 2. How is information in the environment compared with stored representations to allow identification? The first question is related to analytic versus holistic processing. They found that placement of a note within a musical phrase was the most consistent predictor and also explained the most variance. One surprising result was that temporal factors (metrical accent and duration relative to the beat) contributed more to the melody identification that did pitch factors (no significant predictors). Also, the relative importance of contour information at the expense of interval information is surprising, given that past research has shown that listeners are more likely to rely on interval information with familiar melodies and long retention intervals. These results could aid in designing audio feedback, which requires more than two conditions to be identified.

Some research on music perception take a more analytical approach to music perception, generating computational models, which provide powerful tools to reason about design of audio feedback. Abdallah (2012) notes that music is experienced as a phenomenon that unfolds in time and our experience depends on how we change and revise our concepts as events happen, on how expectation and prediction interact with occurrence, and that to a large degree, the way to understand the effect of music is to focus on this 'kinetics' of expectation and surprise (Abdallah, et al., 2012). Abdallah and colleagues are able to define their Information Dynamics Approach to Cognitive Music Modeling by using mathematical concepts such as entropy and establish theoretical values for *surprisingness* in terms of probabilities. After establishing some precise formulas, they derive theoretical values for subjective information dynamic measures. They propose how we anticipate future events. They point out that an event may be surprising but not informative in a predictive sense. This model can be used in a selective phase of composition by specifying a certain temporal profile of surprisingness and uncertainty. The value for predictive information rate (PIR) is low for highly predictive and random streams. A high PIR implies a balance between predictability and unpredictability that causes the observer to continually pay attention to each new observation in order to make the best possible prediction about the evolution of the sequence. With their Melody Triangle interface, complex compositions can be generated by controlling at an abstract level of information-dynamic properties. The user test with the Melodic Triangle sparked a variety of responses, from becoming bored to not having enough time to explore. The center region of the triangle was not enjoyed by one subject and considered 'melodic' and 'interesting' by another, illustrating the complexity of musical perception.

For the purposes of my audio feedback, predictability of the 3-note sequence was desirable in order to be quickly graspable as indication of correct position. On the other hand, the surprise caused by an unpredicted change to the percussion sound can aid in gaining attention of the participant. The Information Dynamics Approach to Cognitive Music Modeling sheds interesting light as a formal analysis of the sounds I chose for the audio feedback.

The therapeutic aspects of music have been extensively studied. Clair (2012) discusses the use of carefully composed music to support movement exercises (Clair, et al., 2012). A different use of music had to be made in my research since I was looking to support stabilization exercises.

Some research has focused on the practical use of entrainment and musical affordances. Krueger (2014) describes the musically extended mind (Krueger, 2014). A common use of music is an atmosphere-enriching sonic additive. Dynamic beat-heavy music can elevate spirits at a party, creating a joyous atmosphere, and compelling listeners to mingle and dance; slower reverent music – at a funeral, for instance – can have the opposite effect, bringing about at atmosphere of quiet grief and remembrance. The use of musical affordances, a term originated in ecological psychology, defined by Gibson (Gibson, 1979).

Krueger asks: “What does music afford the listener?” An obvious but nevertheless important answer is that music affords movement. Unlike non-musical noise in our environment, which may cause a sudden motion, but not sustained motor engagement. Music affords not just movement but, crucially, entrainment. Through entrainment, we are able to provide scaffolding to novel emotional experiences. Our relationship to music seems to be active even when passive listening. Research by Chen (2008) found that subjects who listened to musical rhythms with the knowledge they would be asked to tap along, showed activity in supplementary motor area, mid-premotor cortex and cerebellum (Chen, et al., 2008). These same areas were active in naïve subjects.

The entrainment aspect of music, which is so desired in many contexts, can be disruptive in the core stabilization exercises and cause undesired movement. Therefore, considerable attention should be paid to the dynamics of the sound used in the audio feedback, so as not to invite additional movement other than correcting for alignment. In addition, the reliance on extrinsic feedback may distract attention from internal sensations. While for some people, this reliance could make the exercise experience more pleasant, the long term goal should be to increase awareness of the body and not dependency on extrinsic feedback, whenever possible. Using continuous sound and music to support stabilization raises some issues related to entrainment, induced emotions and arousal.

Many of the sounds we hear in everyday life are not music and some research has been directed to perception of everyday sounds. Gaver (1993) starts by distinguishing *everyday listening* from *musical listening* – both ways of experiencing sound are valid (Gaver, 1993). Everyday listening is rarely addressed in psychology, most research on sound and hearing has focused on musical listening. Sounds are caused by and convey information about the interaction of materials at a location in an environment. Traditional accounts would emphasize the internal processes that mediate between arrival of a sound at the ear and the experience of its source, focusing on transduction, pattern recognition and the like. Computer musicians have used analysis and synthesis (Risset and Wessel, 1999) to understand how to reduce the data from time-varying Fourier analysis so that only the information necessary for recreating a perceptually identical sound is retained for capturing traditional acoustic instruments. While computer musicians are concerned with re-creating the sound of instruments for musical listening, analysis and synthesis to study information for events must be judged with respect with everyday listening. Gaver describes analysis and synthesis for 3 basic-level events: impacts, scraping and dripping. He goes on to describe how to model impact of metal vs. wood bars of different lengths. This research allows abstract sounds to be identified as their likely source in terms of physical objects and events. My investigation with audio feedback falls in the boundary between everyday listening and musical listening.

Research on abstract sounds often discusses alternative cognitive models to explain our perception. Steenson encourages us to think of sound as materials (Steenson and Rodger, 2015). The vertical form of discourse is evident in the field of auditory perception. In attempting to understand how sound is perceived, research has based explanation on cognitive structures residing in observers mind. The indirect and compartmentalized explanation of auditory perception is successful at explaining how listeners process low-level dimensions of sound. An alternative approach is to treat auditory events as whole. We hear things in the world before the sensations that make them up. This can be explained through Gestalt and ecological psychology.

Some research on sound perception related to task-oriented movement has centered on action-perception coupling. Boyer (2015), in his doctoral dissertation, describes action-perception coupling in detail (Boyer, 2015). He reviews the main theories about this coupling from cognitivist to embodied cognition. Boyer highlights the need for research in action-perception coupling to contribute understanding to the sensorimotor learning.

The importance of understanding the potential benefits of using of sound in interfaces has recently surfaced by a wide range of perspectives. Rönnberg (2016) brings our attention to the emotional qualities of sound and music when designing auditory visualizations (Rönnberg and Löwgren, 2016). Interdisciplinary research drawing from music psychology, music cognition and cognitive neuroscience of music, musicology and philosophy of music, may inform how best to use audio to represent data. It has been shown that music conveys emotions. Joyful and happy sections of a musical piece are associated with increased activity in the left frontal lobe. Feeling sad is an emotion associated with loneliness. Psychoacoustics is the scientific study of sound perception: that is the psychological and physiological responses associated with sound. Although proposing auditory information to complement visual displays, Ronnberg touches on a number of useful qualities of sound and music.

Although this section is included in the dissertation, it was not used during the research because sound and music were given less priority at the start. Since much of the investigation evolved around characteristics of the audio feedback, I understood that it would be useful to reference the literature that informs the perception of the music and sound stimuli.

The next chapter describes research related to different aspects of my investigation. I review work related to biofeedback based on motion sensors and research associated with commercial products that use motion sensors to offer solutions for physical rehabilitation, including low back pain. The third section covers music used in biofeedback for rehabilitation.

3
Related work

In this chapter, I cover some of the related research in motion sensors used in biofeedback and 3 commercial products that use motion sensors to provide solutions for rehabilitation and treatment low back pain.

Biofeedback is based a variety of biological signals. Giggins (2013) classifies biofeedback alternatives in two major categories: physiological and biomechanical methods. The biomechanical category includes the use of inertial motion sensors (movement), which are of interest in my research (Giggins, et al., 2013).

3.1
Biofeedback with motion sensors

Biofeedback systems based on motion sensors have often been used in posture control and balance training exercises. Three of the 14 papers I reviewed in this area were related to audio biofeedback, the other 11 papers were related to visual or vibrotactile biofeedback. Dozza investigated different ways to organize audio biofeedback in postural motor learning (Dozza, et al. 2011). Dozza states interest in biofeedback systems to enhance postural stability was renewed due to advances in technology. He defines the three main components that biofeedback design should optimize: 1. The sensor which acquires biological inputs to feedback; 2. The processor, which converts this biological inputs into new information understandable for a user; 3. The interface, which conveys this information to the user. In addition, it is important to determine the amount of information that is actually needed and can be used by the human user. Audio Biofeedback (ABF) has been shown to improve stability by strengthening the closed-loop control of posture without influencing the open-loop (anticipatory) postural control. Further, ABF showed the largest improvement occurred in subjects with bilateral vestibular loss, suggesting that biofeedback can substitute for lack of vestibular information. Comparison between ABF and visual biofeedback showed how encoding of body sway is dependent on the interface (audio vs. visual). They also showed that vibrotactile feedback improves performance, but not rate of learning, to walk tandem eyes closed, suggesting that ABF can be used as sensory substitution or sensory augmentation, but not as a training device with a positive after-effect. It is not clear how specific biofeedback should be used (amplitude and/or direction of alarm threshold) to maximize improvement during sway stance. It is often difficult to determine how much postural stability benefits from biofeedback since it is always superimposed upon large practice effect due to spontaneous motor learning. Dozza experimented with the amount of Medial-Lateral – Center of Pressure (ML-COP) information that was fed back. There were 4 conditions: 1. Both direction and magnitude. 2. Only direction. 3. Only magnitude. 4. Alarm only based on reference threshold. Threshold was calculated based on two standard deviations of the displacement recorded during the 10 seconds before each trial. The threshold value was gradually smaller as subjects practice the task. The ABF sound consisted of a 400 Hz sine wave modulated in volume so that changes in volume could provide information about the ML-COP displacement. All four ABF modes provided sound to the subjects that became more and more unpleasant, the larger the sway. This experiment showed improvement in balance related to use of ABF as compared to no ABF as well as improvement in balance due to learning and integration between natural and artificial (ABF) sensory information. ABF affected motor strategies used by subjects to maintain postural stability on the rotating surface. It is possible that performance immediately after biofeedback is removed gets worse because of dependency on the biofeedback. Dozza (2011) states that visual feedback is slower than ABF and ABF provides the kind of sensory information that the vestibular system provides (body sway velocity and direction with respect to gravity) so its very physiologically relevant, and it is not noisy since it is very highly correlated with the natural physiological inputs related to body sway. Their study showed how both spontaneous motor learning and sensory augmentation by ABF combined to reduce body sway when humans practice balancing on an unpredictably moving surface.

Franco (2013) also provided audio biofeedback to assist in balance improvement in bipedal standing (Franco, et al., 2013). They used a Kalman filter in a smartphone to in their iBalance-ABF. The underlying principle of the iBalance-ABF is to supply the user with supplementary information about the medial-lateral (ML) trunk tilt relative to a predetermined adjustable “dead zone” (DZ) through sound generation in earphones. The DZ is considered to be a zone in which an individual sways while standing, but still does not need any extra information to stabilize upright posture. It is when swaying outside this DZ that an individual need to receive ABF to correct sway to within the DZ in order to stabilize upright posture. The ML direction was chosen since they are most strongly correlated with fall risk in elderly population and the DZ was set to1 degree. The ABF provided a sound while ML trunk orientation was outside the DZ, only to the ear on the side of the inclination. This was considered the “repulsive” mode. The iBalance-ABF interface allowed this to be switched to “attractive” mode, which caused the ABF to towards the ear on the side of the direction of correction. The size of the DZ threshold was also configurable, in degrees: 0.5, 1, 2, 5, 10, 15, and 20. Franco (2013) found their solution improved ML balance in healthy subjects, during tandem stance condition. After the “proof-of-concept” study, they pointed to the need to test against other populations, such as the elderly, respecting individual’s sensory capabilities and deficits.

Horak (2015) researched posture sway and gait rehabilitation with body worn movement monitor technology (Horak, et al., 2015). Their audio-biofeedback consisted of a tone that increased volume with the extent of postural sway (more in the right ear during right sway and in the left ear during left sway). Forward and backward sway were indicated by a high-pitch tone and low-pitch tone, respectively. Every patient with bilateral loss of vestibular function who could not stand on a compliant foam surface with eyes closed without biofeedback could maintain equilibrium with the audio-biofeedback that substituted for the vestibular information. Very little training was required, and the effectiveness of biofeedback was proportional to the amount of vestibular loss and to the difficulty of the task. Horak (2015) conducted another study with patients with mild traumatic brain injuries who had excessive postural sway in stance. Their movement monitor on the belt sensitively measured increases in postural sway when people stood in more challenging conditions, such as on compliant foam, but feeding back, the trunk tilt signal greatly reduced postural sway in every condition, even without practice. Because its not possible for therapists to manually provide quick, accurate feedback about postural sway, biofeedback can supplement balance training. Comparing balance training to the Supine Bridge exercise, the relative instability of the upright stance provides more room for improvement and for benefiting from adequately provided biofeedback.

Motion sensors, in wearables, have also been used to assess the quality of fitness exercises (Velloso, et al., 2013), to classify body postures and movements (Ugulino, et al., 2012) and to support collaboration in elderly monitoring (Ugulino, et al., 2012).

A related work that did not involve motion sensors but measured position of the spine with a novel sensor was the t-shirt developed by Sardini (2015). The t-shirt was instrumented with an inductive sensor (copper wire and separate circuit board) to monitor the curvature of the spine. It would be interesting to combine this technology with inertial sensors.

3.2 Related commercial products

Three commercial products have been identified that address related aspects of the StableBelt research. They were brought to my attention by scientific papers published recently (Costa et al., 2013; Kent, et al., 2015; Hügli et al., 2015). All three products make very different uses of feedback during exercises and provide compelling solutions to rehabilitation and treatment of low back pain. They tend to rely on visual feedback, through computer games, to improve motivation. Extensive information on the products available at their web sites: Riablo, Italy (http://www.corehab.it/, accessed on: January 24, 2016); DorsaVi, Australia (http://dorsavi.com/, accessed on: January 24, 2016); Hocoma, Switzerland (https://www.hocoma.com/, accessed on: January 24, 2016). Riablo has a product called CoRehab, that combines games and orthopedic rehabilitation (Costa, et al., 2013). This product claims to support over 170 exercises. In order to compare to my solution, I would need to understand what these exercises are. From the marketing literature, it appears that their associated computer games is highly visual and do not explore feedback based solely on audio.

DorsaVi has a product called ViMove that is specifically designed to assist in assessment of low back pain (Kent, et al., 2015). It has the capability to synchronize data gathered from sensors with video for analysis. A concise description of their capabilities, extracted from their web site, is presented below:

> "ViMove™ is a wireless sensor technology that objectively measures human movement and turns it into actionable data. Wearable motion and muscle activity sensors record data at 200 frames per second. During flexion, what's the breakdown between pelvic movement and lumbar spine movement? How does your patient progress from repetition to repetition? How about when they're fresh vs. fatigued? ViMove™ provides visual, objective, easily interpreted data to improve your assessments, choose and manage treatment options, and document therapy progress for patients, referral physicians and insurance companies. In a recent randomized controlled trial, patients treated with ViMove™ for ten weeks were more than 3X more likely to have clinically important improvements (>30% over baseline), in reduced back pain and 2.5X more likely to have clinically important improvements in activity limitation vs. patients treated with guidelines based care at 12 months."

Besides providing detailed assessment of spine mechanics, the ViMove product also includes a wearable device that provides warnings during daily activities that could cause pain or injury.

The third product Valedo, from Hocoma, also targets exercises for the treatment of back pain (Hügli, et al., 2015). Valedo comes with three sensors and claims to support 45 therapeutic exercises. Valedo also supports self-supervised exercise at home. From the marketing literature, it appears their solution is based on visual feedback and does not explore feedback based on audio only.

Unfortunately, I found no details regarding the exercises in any of the products materials or research papers to allow a comparison with my research results. The papers in reference were published by physical therapists outside the companies and all showed positive results.

3.3
Music and feedback

This section was added as a request by the advisory committee during the defense and is not referenced by the rest of the document. Although the focus of this dissertation is core stabilization exercises, some of the research on sonification of movement may help shed light on the use of sound and music to support core stabilization. Music has also recently being explored in biofeedback to control physiological aspects.

Newbold (2015) provides a musically informed framework for sonification of movements in self-directed chronic pain physical rehabilitation (Newbold, et al., 2015). The framework proposes mappings for: melody, harmonic and cadential structure, texture and rhythm. The two main goals for the framework are to decrease pain avoidance anxiety and encourage movement. Although this framework appears promising, the paper does not describe how it will be implemented (i.e. sensors used, audio generation). In contrast with my investigation, Newbold (2015) proposes music structures for generating feedback to motivate movement in chronic pain patients, they are not concerned with stability.

The research by Newbold and colleagues builds on previous work by Singh (2014) which implements some of the music feedback concepts using mobile technology (Singh, et al., 2014). An interesting aspect of the work by Singh and colleagues is their research approach, which included: Role-play with physiotherapists, interviews with chronic pain patients and physiotherapists, focus groups, CP blogs and forums, and observations of physiotherapist-led group sessions.

The research in applying music associated with biofeedback to control physiological aspects is a recent development. Bergstrom (2014) states few studies report explicit use of a musical feedback signal for biofeedback (Bergstrom, et al., 2014). She lists 3 different studies related to regulation of physiological processes, such as heart rate and respiration. Another used for training stroke patients in reaching and grasping an object, both using a predefined music across participants. Commonly, in biofeedback with sound, the feedback signal consists of a continuous tone of fixed timbre, whose frequency and/or amplitude are mapped to the underlying physiological measure, for example pitch increasing with chest expansion, or volume decreasing to reflect a decrease in tonic skin-conductance level. Single short tones commonly reflect events, for example heart-beats. Stereo panning or 3D audio may indicate the location of the conveyed parameter. In established biofeedback practice, when physiological signals are conveyed sonically, as well as in auditory display, and more generally where information is conveyed through sound, the process involved is termed sonification: “ the transformation of data relations into perceived relations in an acoustical signal for the purposes of facilitating communication or interpretation”

(Kramer, et al., 2010). Bergstrom did not find any studies that directly compared music biofeedback protocols to biofeedback protocols that do not use music, or to the effects of music alone. They report on what design considerations are important in devising a musical biofeedback protocol. One of the considerations for designing musical biofeedback is the difficulty in noticing small tempo changes in music (Thomas, 2007). The window of four beats was selected for account for heart rate measures. Many compromises were made in order not to make the signal un-musical. The detailed composition criteria for the intended purpose resulted from an exhaustive review of the literature on music perception (Ball, 2010; Sloboda, 2005). Their compositions used neutral, classical orchestration, and did not include lyrical content. A number of other criteria went into the compositions to increase its potential to elicit arousal or relaxation. In particular, they avoided similarities to popular compositions. While discussing results, Bergstrom lists 4 possible effects desired when choosing an approach for music selection to be used: 1. the universals of arousal modulation and entrainment; 2. the attention-drawing effect of music; 3. mood regulation; 4. to entertain the participant, thus maintaining active engagement. Their results show no significant difference between the sonification biofeedback and the combined music biofeedback. One potential explanation is that for this protocol there is no benefit in choosing music biofeedback over sonification biofeedback. Bergstrom states the importance of the biofeedback technique to use a signal that has reinforcing properties, for helping participants in learning how to gain control over their physiological states. Given the complexities that recorded music brings to the simple task of correctly maintain Supine Bridge position, the results from Bergstrom's investigation should be carefully considered in my research.

After reviewing the related work, in the next chapter I discuss the method used for this research, namely action research. A method based on taking actions in the world, observing and reflecting the outcome of these actions.

4
Methodology

In this section, I describe the research methodology that was used, namely Action Research, and relate it to the research questions that guided this investigation.

4.1
Research questions

Exercises for low back pain, such as the core stabilization exercises, can be challenging to learn and to practice routinely. Can audio feedback based on motion sensors help improve the rehabilitation experience? How should this audio feedback be configured to accomplish this goal? How does music behave in this environment?

In this research, I propose an exploration of audio biofeedback for the core stabilization exercises that would make practicing the exercises more pleasant, while supporting the precision required for benefits to take place. We know that music therapy provides benefits for physical rehabilitation (Clair, et al., 2012). How could a few of these benefits be gained through audio biofeedback in stabilization exercises used in treatment of low back pain? I would like to explore possibilities in order to provide some suggestions for designing audio feedback, as well as, inform future research.

4.2
Qualitative research

Data was collected through logs, audio recordings, transcripts (interviews) and videos, always with the consent of the participants. Data was analyzed using Atlas.ti (Friese, 2014). The relevant comments from the semi-structured interviews were grouped in categories and assigned codes. These categories are then discussed in relation to the original goal of the investigation – gain preliminary understanding of how ABF affects the execution of the Supine Bridge exercise. The graphs derived from the log data were reviewed for general trends and overall patterns.

4.3
Action research

This investigation uses action research as the research method. In action research, a problem in a real world context is identified. Actions are planned and performed to attempt to solve this problem and results of these actions are observed and reflected upon (Herr & Anderson, 2005). The problem I identified was how some low back pain patients have difficulty in performing stabilization exercises. The solution I provided in the first cycle was to offer audio biofeedback based on a wearable with motion sensors – StableBelt. This audio biofeedback, initially, was based on instrumental music. The variation of the loudness would indicate whether patient was in the correct position for the exercise. The StableBelt consisted of the motion sensor integrated with a microcontroller, a plastic case, an elastic belt and a laptop computer.

The real world context for the action research was the environment where the core stabilization exercises are being performed. It could be a physical therapy clinic, physical therapy department in a hospital or the patient's home, depending on the rehabilitation stage. In this research, an attempt was made to conduct the research at a clinic or hospital. After considerable effort reaching through personal contacts and initial dialog, no partnerships were established. I proceeded to host the action research at a room in the university. Some realism may have been lost in this strategy. As a physical therapist with experience teaching the Supine Bridge exercise, I endeavored to maintain the realism of working at a clinic and organized the room to resemble places that I have worked before. The other aspect of the research was to understand the use of the prototype in the home environment. This research was also conducted in the same room at the university. Given the stage of the prototype, time and logistical constraints, this was felt to be a reasonable trade-off.

The action research model used in this research consists of four phases: plan, act, observe, and reflect (Kemmis & McTaggart, 2005, apud Filippo, 2008), as shown in Figure 5.

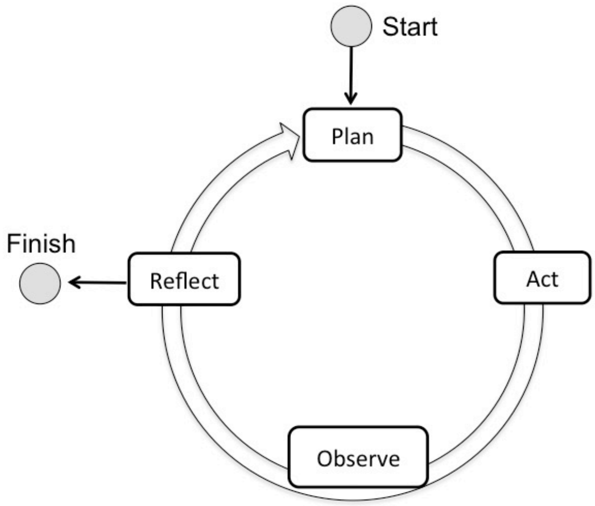


Figure 5 - Phases of Action Research cycle

During the plan phase, the interventions are planned, including what will be prototyped to support the intervention. The act phase is when the intervention takes place. In the observe phase, data is collected and analyzed. The reflection phase organizes what was learned during the cycle and sets the direction for the next cycle, if another cycle is necessary and feasible within the research project constraints.

In action research, there are a few different roles the researcher can position himself relative to the organization where the problem is situated (Herr & Anderson, 2005). He can be an outsider collaborating with a practitioner. He can be an insider, participating directly in the activities being investigated. My training in Physical Therapy, allowed me to participate as an insider in the action research, described in this dissertation.

4.4 Participants

Participants were recruited from the university where the research took place via opportunistic recruitment and referrals. They were students the university, with the exception of one personal contact. All were not suffering from low back pain and able to perform the SB exercise. As I began to plan the first cycle of the research, it became clear that I should recruit participants that were not suffering from low back pain. Since I was beginning to understand the issues involved with the technology and its effects, it would not be appropriate to risk working with participants with pain, at such an early stage. After I gain knowledge regarding the technology and its effects on healthy people, there will be a stage when it will be appropriate to test a future version of the StableBelt with patients suffering from low back pain. No participant showed hearing impairment and all were able to hear the audio feedback adequately. All participants were briefed on the procedures, received training on how to use the StableBelt and how to perform the exercise. Every participant signed an informed consent form that is included in Appendix C – Research Protocol (in Portuguese).

4.5 Research ethics

The research protocol of this project was submitted to and approved by the Ethics Committee of PUC-Rio. It presented the broad lines of research and the critical points about the ethics of this study. I provide it here as an appendix to this dissertation with the dual purpose of: first, give the reader the appropriate evidence of the ethics evaluation of this research, which, I believe, can contribute to its reliability; and second, to offer some practical support to those who may need to conduct research studies in similar circumstances (see Appendix C – Research Protocol (in Portuguese)).

5
Research cycles

In this chapter, I present the five action research cycles that were part of this research project. The first cycle was focused on getting the StableBelt prototype working with recorded instrumental acoustic guitar music as audio biofeedback. This prototype was tested with one participant. The second cycle was intended to enhance the StableBelt with additional sensor data to be used in the Audio Biofeedback generation. I explored flex sensors and FSRs. During the second cycle, interviews with two physical therapists led me to prototype a solution with 2 motion sensors communicating with the computer simultaneously to generate audio biofeedback. Given the programming challenges encountered and the inability to estimate a completion date for the prototype with 2 motion sensors, I decided to discard this prototyping effort. No user tests were conducted during the second cycle. In the third cycle, I resumed the single sensor strategy and focused on the type of audio being generated. The audio biofeedback was based on piano and drum simulations. During this cycle, I conducted a test with 5 participants. The fourth cycle included an automated prototype that could be used in the context of a patient at home without supervision from a physical therapist. In the fourth cycle, I conducted a test with 8 participants. The fifth cycle focused on a new design for the belt. This design was started during a workshop at Museu de Arte do Rio (MAR). It was intended to address comments from previous tests regarding lack of comfort of the belt. Since the new design did not modify aspects of the audio biofeedback, a decision was made not to conduct a user test for this cycle.

Each cycle can be summarized in terms of high-level abstractions that were present in the prototype (Figure 6). The three prototypes that were tested also can be summarized according to high-level abstractions that defined their overall flow (Figure 7).

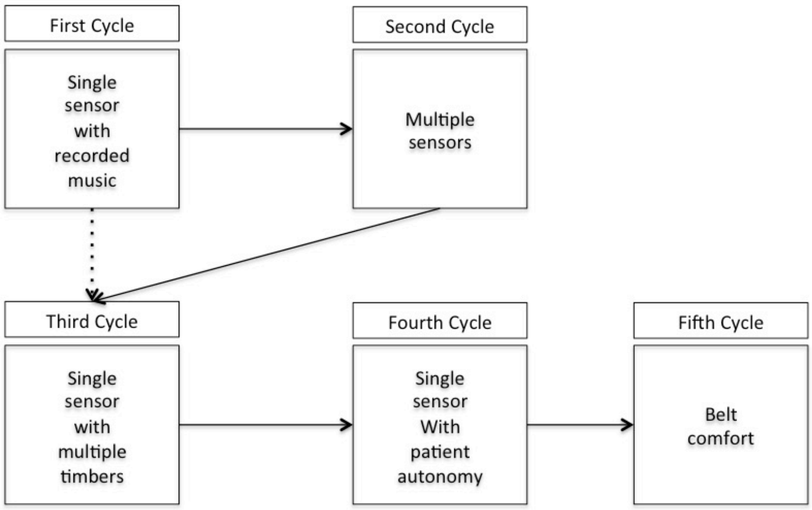


Figure 6 – High level abstractions present in the prototype and how they change through the action research cycles

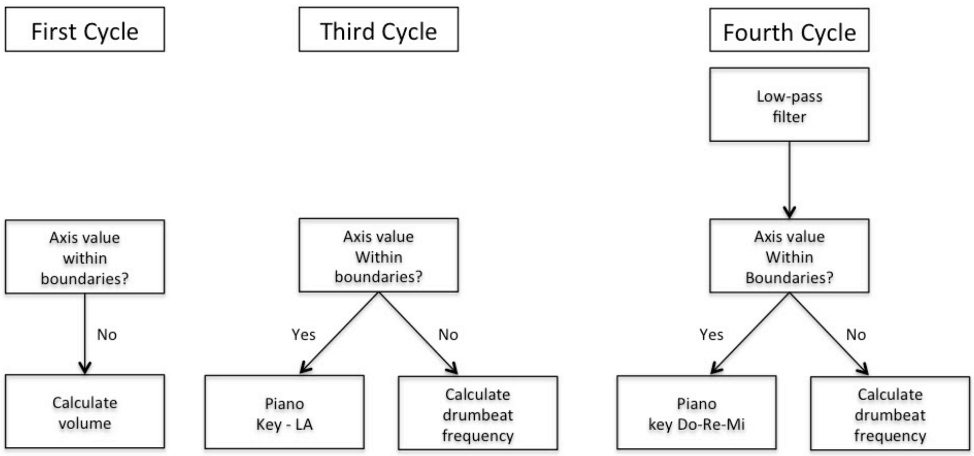


Figure 7 High level abstractions present in flows and how they change through the action research cycles

The first cycle provided the initial prototype code and this base of code was used in later cycles. Only the second cycle used a different base of code.

The next section describes in more detail the first cycle of the action research and the preliminary test conducted in this cycle.

5.1
First Cycle – Recorded music

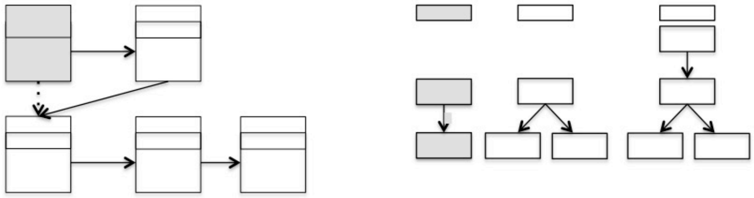


Figure 8 – The first cycle in context

During the first cycle, I started the exploration of how the StableBelt behaves in conjunction with the SB exercise. I will describe the four phases of the action research cycle. Only one participant took part in the user test for this cycle. The focus of this cycle was to get an initial prototype working and understand the test procedures.

5.1.1
Plan

My intention with the first cycle was to get a preliminary understanding of how the audio biofeedback generated by the motion sensors affected the execution of the SB exercise. The audio biofeedback used in the first prototype was based on instrumental acoustic guitar music. The loudness of the music was modulated according to the distance of the lumbar spine from the correct position during the SB exercise. A semi-structured interview was not conducted during the first user test. The reflection phase of this cycle was based on reviewing the motion sensor data recorded in logs and displayed in associated graphs. Semi-structured interviews were conducted during the second and third test.

5.1.1.1
Recorded Music as Audio Biofeedback

In the first prototype, the audio biofeedback was based on recorded music. I searched for timbres and genres that were soothing and simple enough to serve as possible source for the audio. The timbre selected was acoustic guitar. To minimize distractions and keep the signal as simple as possible, the music played was instrumental without vocals or lyrics.

One concern with recorded music is the lack of control. In the first prototype, the only controlled parameter in the audio biofeedback was the loudness. How the melody affects the perceived loudness is one of the complicating factors of recorded music for feedback. The audio biofeedback is being used to inform participants of possible corrections in the SB position. To be effective, rapid cognition of this information is required. The goal of providing audio biofeedback that is pleasant has to be balanced with its effectiveness. Considering some level of attention is necessary to perform the exercise correctly, if the music used induces a high level of relaxation, the quality of the execution could be compromised.

The music loudness was modulated to inform the participant regarding the correct alignment during the SB. If the participant was within a margin of the ideal alignment, no changes to the loudness would occur; it would be played at a reasonable maximum loudness, which was adjusted at the start of the session for each participant. The value for the margin was based on tests with the accelerometer placed on a static surface. I collected data for the variation (noise) of readings from the accelerometer while it was not moving and derived a value for the margin that I considered to be the best precision that could be offered by the audio biofeedback. Deviation from the goal beyond the allowed margin would cause the loudness to lower by a ratio relative to the distance of the margin. This goal value was set at the beginning of session for each participant.

5.1.1.2
Verbal Commands

In this cycle, I remained in the room with the participant and guided the execution of the repetitions of the exercises through verbal commands. The commands were: 1. to start the exercise by raising the hips; 2.to maintain position once reached alignment; 3.lower hips and rest, once the duration of exercise had elapsed (22 seconds). In addition to verbal commands, the beginning and ending of the 22 seconds of the static portion of the SB were also signaled by changing the song being played. This provided extra information regarding how much attention was given to the audio biofeedback and how much the participant could perceive differences in the audio. All songs had similar characteristics; depending on the level of attention, the transition, from one song to another, may not be recognized. The participant would execute the SB exercise 6 times and would be informed when he completed the series.

5.1.1.3 Limitations of the Audio Biofeedback

Only one motion sensor axis was mapped to the ABF. This axis informed the participant the spinal alignment in the sagittal plane. The corrections relative to the body were anterior and posterior movements of the spine. Another possible dimension of feedback would be rotational alignment (i.e. differences between the heights of right and left hip). A 2-dimensional mapping to the ABF would increase the complexity of the audio signal and might make use of recorded music not feasible.

5.1.1.4 Issues related to continuous tones

During this cycle, I also experimented with continuous tones based on different frequencies. While using continuous tones, I experienced continued buzzing after the sound stimuli had stopped, suggesting it could cause hearing impairment or at least an unpleasant experience. This served as a warning to not invest additional resources towards this strategy for audio biofeedback. Soon after these experiments, I noticed the speaker on my MacBook was not functioning properly and it could no longer handle some acoustic ranges.

5.1.2 Act

In this section, I describe the initial prototype and the test that was conducted with it. Components of the prototype are explained, with an effort to separate general guidelines from implementation details to support the recoverability of the investigation in a context where the specific technology may have changed.

5.1.2.1
StableBelt: The prototype and its components

The physical components of the StableBelt are: motion sensor, a protective plastic case, an elastic belt and a laptop computer. Keeping the cost low was a design priority. During the second semester of 2015, all parts of the prototype together cost less than 50 US Dollars, except for the laptop computer. I used a MacBook Air, which I already owned prior to the research project.

The motion sensor is a tri-axial accelerometer embedded in microcontroller called LightBlue Bean (Figure 9). This microcontroller also provides Bluetooth support and libraries to simplify acquiring sensor data and sending data via a serial interface.

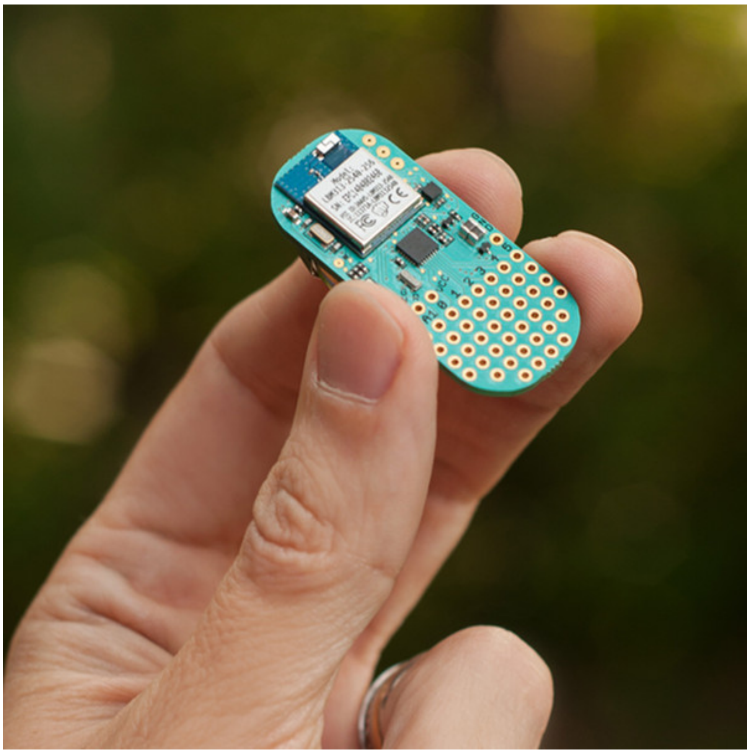


Figure 9 - The LightBlue Bean from PunchThrough Design

The LightBlue Bean specifications appear in: https://punchthrough.com/bean/guides/getting-started/tech-specs/, accessed on: Jan 23, 2016.

The microcontroller was placed in a protective plastic case, which was printed with the SecondLab's 3D printer (Figure 10). The 3D model was designed to hold the LightBlue Bean microcontroller and downloaded from the Thingiverse repository: http://www.thingiverse.com/thing:390134, accessed on: Jan 23, 2016.

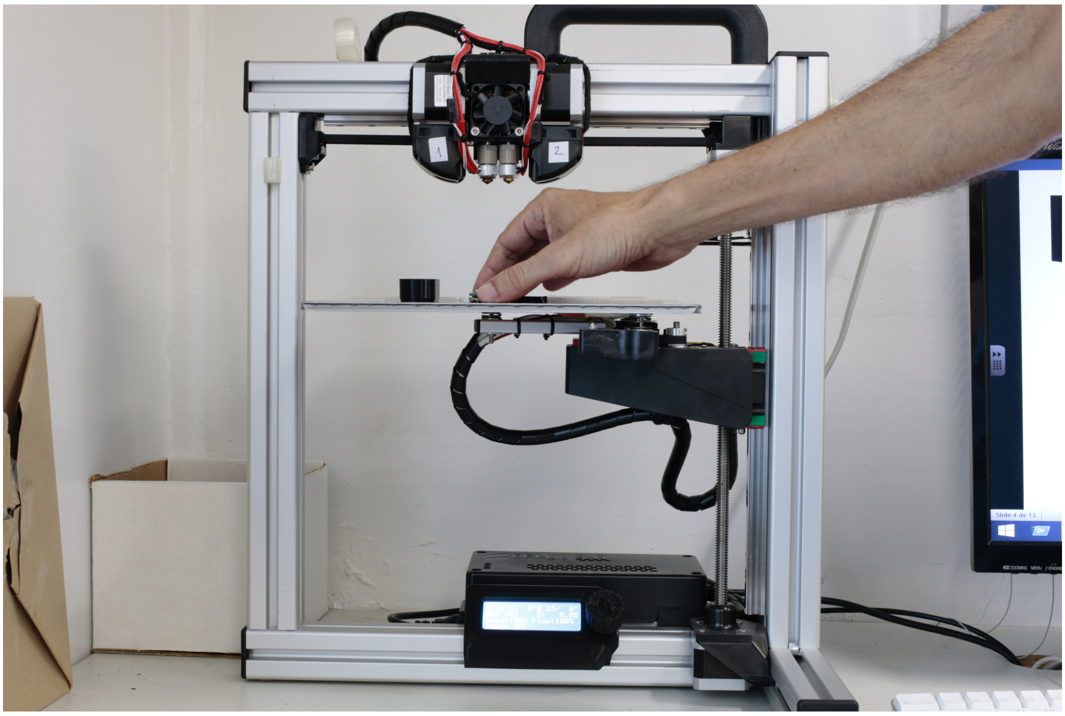


Figure 10 - The plastic case and the 3D printer

The plastic case was placed in a pocket on an elastic belt that was fastened with velcro around the participant's waist. The initial placement of the velcro was inadequate for participants with waists below certain size. This limitation was identified during the third cycle and may have contributed to inadequate perception of the audio biofeedback during the first test. The elastic band and its pocket were positioned so that the motion sensors were approximately near L3 (third lumbar vertebrae) on the spine.

The rate of the accelerometer data being read and recorded varied between 10-12 Hz. The relatively low rate, in my understanding, was due to the overhead of the serial interface running over the Bluetooth protocol. However, I felt this rate was adequate to test how participants reacted to the audio biofeedback.

In order to provide real-time biofeedback, a simple threshold detection approach was used. First, the value from the selected axis was compared to the upper and lower thresholds. These thresholds were calculated by adding and subtracting the margin value, respectively, from the goal value. If the value fell outside these boundaries, the distance to the closest threshold was multiplied by a constant, in order to generate the appropriate audio loudness. In the first prototype, biofeedback generation was based on raw accelerometer data. In the fourth cycle, a low pass filter was applied to the data before biofeedback generation.

The software for the laptop computer in the first prototype was implemented by a Processing program with the following abstractions:

- Initial setup procedures
- Handle incoming data
- Draw visual feedback
- Test thresholds
- Calculate loudness, if necessary
- Play sound files using Minim
- Time duration of exercise
- Write log header
- Write raw accelerometer data in log
- Closing procedures

Figure 11 - First StableBelt prototype being used in the Supine Bridge exercise

The StableBelt was placed around the waist with the microcontroller near the lumbar spine (Figure 11). The microcontroller is placed in the plastic case (Figure 12). This case resides in a small pocket on the elastic band (Figure 13).

Figure 12 - Physical components of StableBelt: LightBlue Bean microcontroller, black plastic case, and white elastic belt, with pocket.

Figure 13 - Plastic case being placed in the elastic belt.

5.1.2.2
Serial Interface

One of the attractive characteristics of the LightBlue Bean microcontroller is its simplified support to handle Bluetooth communications. Programs communicate with the Bean using a serial interface (Figure 14).

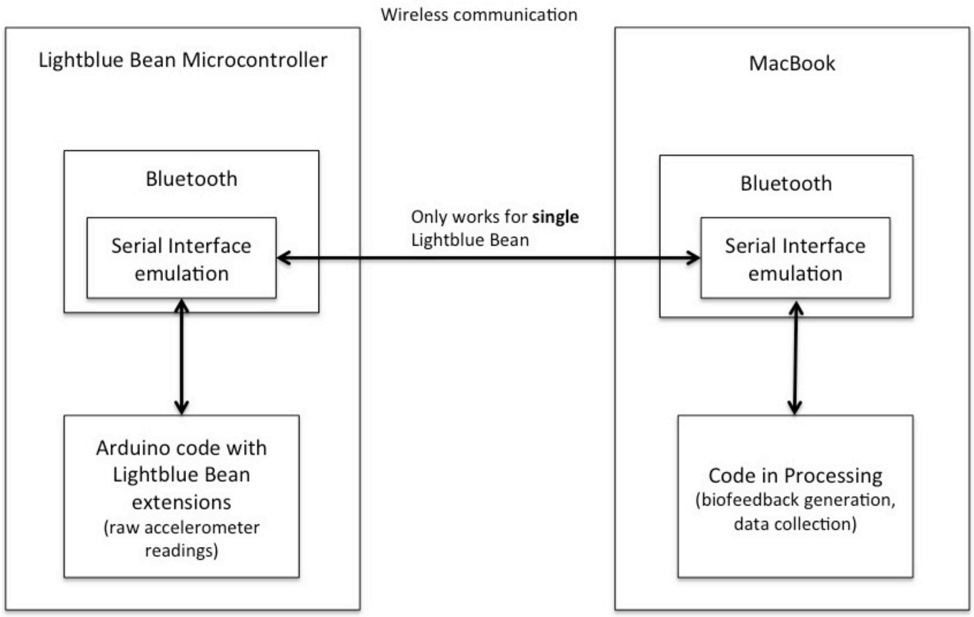


Figure 14 - Different components of the wireless communication used in single motion sensor prototypes

The serial interface limits the communication to a single sensor. In 6 lines of code, a reading from all 3 axis of the accelerometer can be retrieved from the serial port and placed in an array (Figure 15). The data comes in triplets.

```
void draw() {
  while (myPort.available() > 0) {
    myString = myPort.readStringUntil(lf);
    if (myString != null) {
      myString = trim(myString);
      tmpSensors = int(split(myString, ','));
      for (int sensorNum = 0; sensorNum < tmpSensors.length; sensorNum++) {
        if (sensorNum > 2) break; // strange bug causes exception
```

Figure 15 – Code to read data from accelerometer via serial interface

Occasionally, data arrives corrupted and some checking is required to avoid erroneous feedback. These erroneous lines are apparent when looking at the logs, which contain the raw data. A few logs had a high percentage of these garbage lines. I was unable to find any patterns or causes for these anomalies.

5.1.2.3
Audio Support

To generate the audio based on recorded music, I used the Minim library included in Processing, version 2.0. With this support, the code to enable the playback of audio files required only few declarations. The code to play and pause audio files was also succinct. The Minim library is well documented. More information is available on: http://code.compartmental.net/tools/minim/, (accessed on: Jan 23, 2016).

Four Waveform uncompressed files (.WAV) containing the instrumental acoustic guitar music were identified, containing on average four minutes of music.

5.1.2.4
The first test

In the first cycle, one volunteer participated in the test. He had no experience with StableBelt, prior to the test. As mentioned before, it would not be appropriate to have a participant suffering from low back pain at this stage of the research. The participant was pain free and able to perform the SB exercise.

The session started with a brief introduction to the setup, instructions on how to perform the SB exercise and what to expect from the audio biofeedback. Next, the participant executed the SB exercise three times without ABF, while being manually guided for correct alignment, respecting any restrictions due to discomfort or pain. These initial repetitions were used to collect data for calibration. I calculated a mean of the Y-axis for the three trials, using Microsoft Excel. This value was used as the goal for the ideal position to be maintained during the repetitions of the exercises. This task was streamlined for the third test, requiring a single command and only 3 seconds of data to establish the goal value.

After establishing the goal value, the participant executed the SB exercise 6 times, being guided verbally when: to raise the hips, to maintain position, to lower hips, and to rest. He was instructed not to expect ABF during the last 3 repetitions. In this cycle, a separate execution of the program had to be started manually for each execution and another command to start data collection, when I identified that participant had reached the correct alignment. The presence of audio biofeedback was also a parameter that had to be manually modified in the source code prior to the execution of the third repetition. This manual steps and counting required extra attention and could be a source of errors.

I reviewed the information gathered for the StableBelt with the first participant and decided there was enough data in this test to continue to enhance the prototype and to make additional changes before recruiting more volunteers.

5.1.3 Observe

For each repetition of the SB exercise, a log was written in comma-separated format (CSV). Each log contained header information with date and time of when the log started, whether audio biofeedback was present, the goal and margin used to calculate the audio biofeedback, the accelerometer axis measured to generate the audio biofeedback and accelerometer data with labels when the period of 22 seconds started and ended, an additional column registered what loudness was calculated for each reading. For the SB exercise and the orientation of the motion sensor relative to the spine, the Y-axis was always used. These values are compared to the goal and margin values listed in the header section at the beginning of the log. These logs were reviewed using Microsoft Excel in the following days.

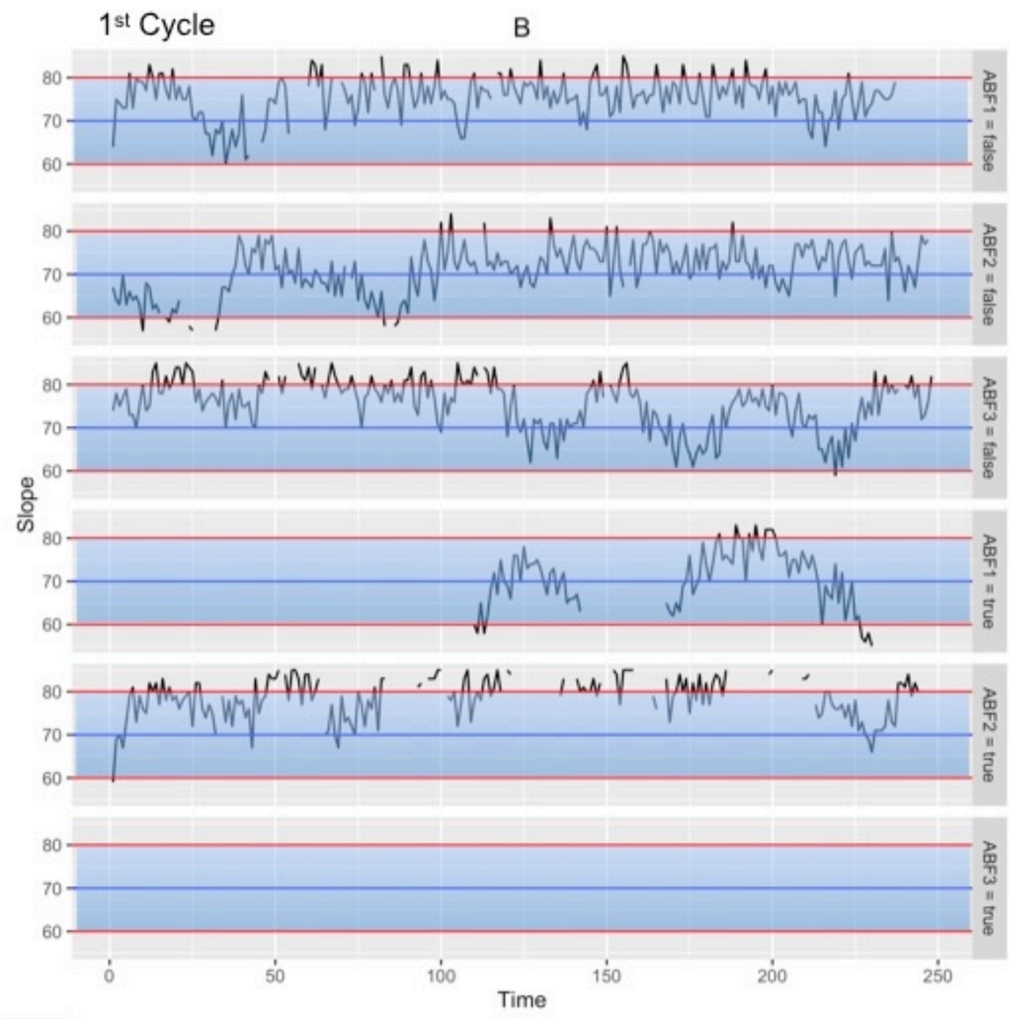


Figure 16 – Graphs of data from participant in first test. Top 3 lines represent repetitions with no ABF and bottom 3 lines represent repetitions with ABF.

There was considerable improvement between first repetition and second repetition with ABF (Figure 16). The missing data for the third repetition would show whether the trend was likely to continue. However, both repetitions had more time outside the margin than the 3 repetitions without ABF. When performing the exercise without audio biofeedback, the participant was mostly within the margin of correct alignment with occasional short periods when he was outside the margins. The third repetition without ABF shows a distinct pattern; the participant was fairly stable for the first half, and then showed larger slow movements within the correct threshold for the second half.

5.1.4 Reflect

When reviewing the graphs, the participant was less stable, moved more, when he tried to maintain position while receiving ABF. When no ABF was provided, he was more stable and moved less during the exercise. More importantly, the relatively long time the participant took to reach the correct position after the ABF lowered the volume to indicate incorrect alignment, suggests the participant did not perceive the changes or did not understand what information was being conveyed by the ABF. Given this evidence, one possible improvement for the ABF would be to use distinct sounds to inform correct and incorrect alignment.

According to my observation, performing the SB exercise seemed to require little effort and he showed not signs of fatigue, for this participant. There was no video recording of this test, making it impossible to further analyze the details of this session. Given the overall trend present in the data, the participant may have been exploring with different positions to understand the behavior of the ABF.

The maximum loudness of the music was an aspect that did not receive adequate attention. Part of the training received by the participant at the start of the test could include a moment when participant hears the music played at maximum loudness to understand the target level to aim during the exercise. I was concerned with the overall duration of the complete session. How much time to devote to training and to the actual test is an aspect of the test procedures that justifies careful consideration. The change in quality of execution from the 1st to the 2nd execution of the exercise raises the question whether, a few more training repetitions would significantly improve the 3 initial recorded repetitions with ABF. The six repetitions in the order they were organized - having the first 3 consecutive repetitions be with ABF and the last 3 without ABF - could allow for some participants to improve with practice and perform better on the last three repetitions. This may have been combined with more focused attention and use of intrinsic feedback and proprioception, to favor the performance of the last 3 repetitions. Another possible consequence of this structure would be that participants would be more tired during the last three repetitions, however, the data does not seem to support this scenario. The structure of the test may have contributed to the limitations of this investigation.

During the first cycle, I was in the process of understanding the procedures for how to conduct the test. There were mistakes in the handling of the prototype, which resulted in missing one exercise repetition with audio biofeedback. The log for the 3rd execution was missing the tag for the start of the execution, suggesting I did not issue the command to tag the beginning of period of stabilization of the SB exercise. Only in the fourth cycle when the procedures became automated, it was possible to see the extent of how error prone the procedures, in this first cycle, were.

After reviewing the information gathered for the StableBelt with the first participant, I decided there was enough data in this test to continue to enhance the prototype and to make additional changes before recruiting more volunteers. In retrospect, it became clear the importance of having a semi-structured interview at the end of the session. Some questions regarding the experience of this first prototype remain unexplored. Unfortunately, the importance of the semi-structured interview only became apparent as the prototyped evolved.

This preliminary test suggests that the perception of changes in recorded instrumental guitar music may be too complex, and volume changes alone relatively too subtle, to serve as an efficient form of audio biofeedback for the SB exercise. The next cycle should consider simplifying the audio biofeedback. One possible strategy to simplify the audio biofeedback and make it more understandable would be to include two distinct timbres; one timbre for correct alignment and another for incorrect alignment. This strategy was implemented in the third cycle of the action research. The next cycle focused on multiple sensors in order to gain additional information to be used in the audio biofeedback and extend the StableBelt to support more types of core stabilization exercises.

5.2
Second Cycle – Multiple Sensors

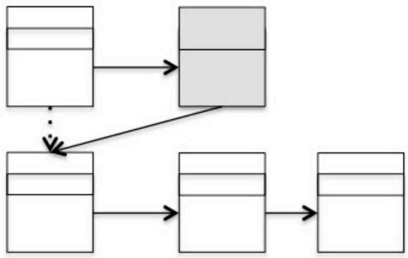


Figure 17 - The second cycle in context.

In this cycle, the use different sensors were explored and a prototype was created to enable 2 LightBlue Bean's to communicate simultaneously with the computer to generate the ABF. This prototype remained incomplete due to challenges described in section 5.2.2 – Act.

5.2.1
Plan

During the reflection phase of the previous cycle, the need for simpler audio elements in the biofeedback was identified as a possible direction for continuing the research. However, knowledge gathered during interviews with physical therapists, together with the possibilities presented by working with multiple sensors, made changes to the audio aspects of the biofeedback a lower priority. The modifications to the audio biofeedback were postponed to the third action research cycle. The interviews occurred in parallel with exploration of different sensors during this planning phase.

Early in this phase, I investigated options to add new components to the StableBelt. The SecondLab had flex sensors (Figure 18) and Force Sensitive Resistors (FSR), see Figure 21. In order to evaluate the sensibility of these sensors, I created 2 breadboard prototypes. While working at the prototypes, I reasoned how these additional components could support core stabilization exercises.

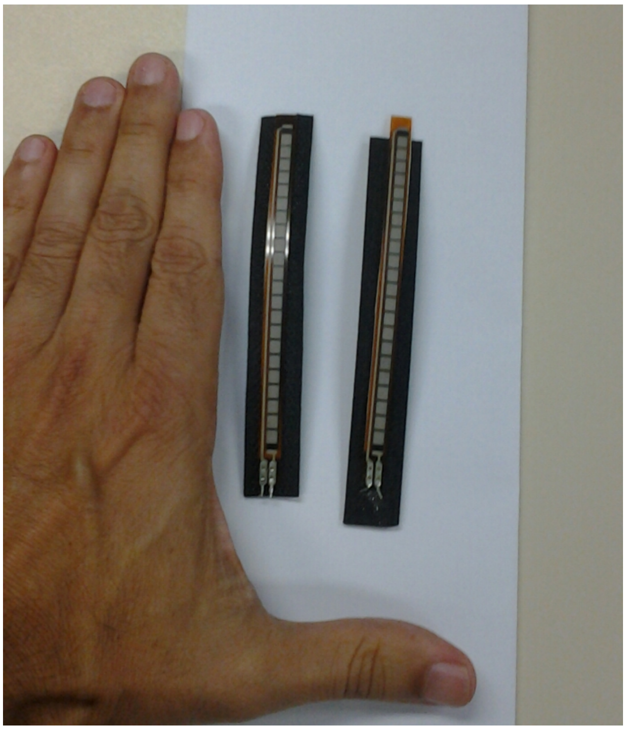


Figure 18 – Flex Sensors

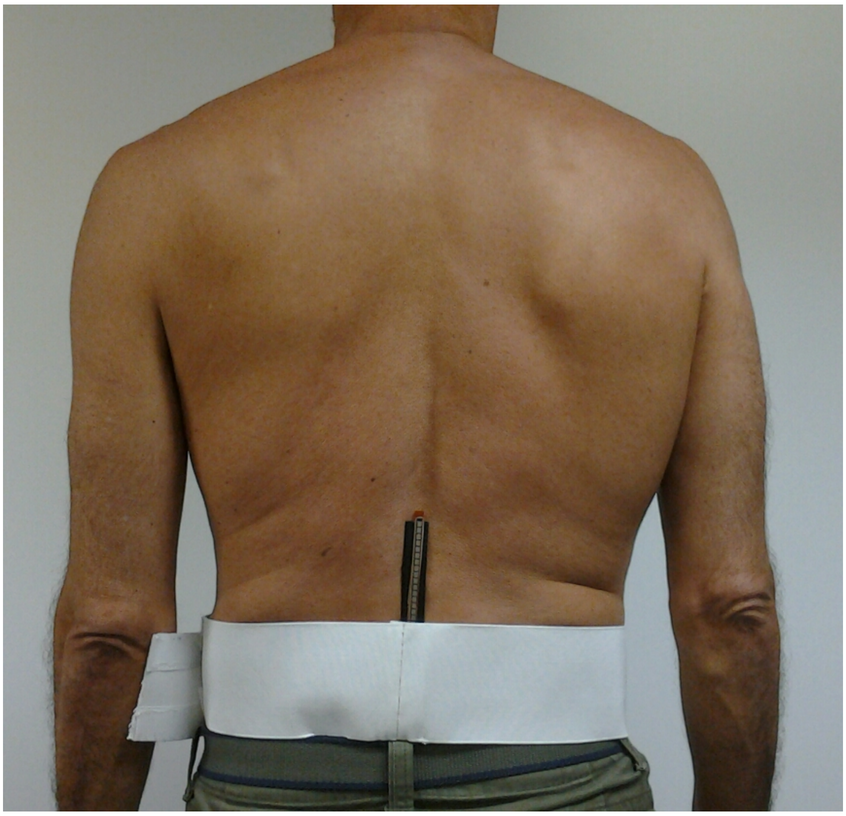


Figure 19 – Flex sensor for neutral spine

The first approach was to configure the flex sensor to assess maintenance of "neutral spine" during the exercise. Two problems were identified with this configuration. The flex sensor only measured flexion in one direction. Since the spine flexes and extends, it was unclear how to implement this capability. I considered using two flex sensors facing opposite directions. This placement could risk breaking the sensors. The second issue concerned the sensor and the anatomy of the region. The lumbar spine often has a deep valley and it was not clear how to attach the flex sensor to this region and have the sensor follow closely the movements of the spine (Figure 19). No adequate solution to these obstacles were found during this research.

A second approach was to configure the flex sensor to assess the capacity of the participant to execute abdominal hollowing. The challenge of how to attach the flex sensor to the waist without loosing contact when abdominal hollowing occurred was also present in this configuration (Figure 20). No adequate solution was found to this obstacle during this research.

Figure 20 - Flex Sensor for abdominal hollowing procedure

In parallel, I explored how the FSR might be used to capture palpation. Palpation is an important aspect of physical therapist's work, when teaching core stabilization concepts, and support for palpation could be useful. After testing the sensibility of our FSR, via breadboard prototype, I experimented with how to place the sensor in relation to fingers of the physical therapist (Figure 21 and Figure 22).

Figure 21 - Force Sensitive Resistor to sense palpation pattern

Capturing palpation could be used in association with machine learning to teach the system to classify correct performance during the SB exercise, for example. Low pressure or no pressure could be associated with motion sensor data for correct alignment. Higher pressure could be associated with incorrect alignment. However, machine learning generally requires a large number of examples to train the system. The requirement for generating a “palpation dataset” was the primary obstacle to implementing a solution for capturing palpation with an FSR.

Figure 22 - FSR for palpation of abdominal hollowing procedure

While different types of sensors were being explored, interviews were conducted with two physical therapists: Denise Tenius and Lilian Ponzoni. Both therapists were actively working with segmental stabilization in the treatment of low back pain. Both therapists suggested that biofeedback during standing exercises, such as squatting, would be very useful to complement their work with patients. Given their extensive clinical experience, I decided to investigate how to support standing exercises with the StableBelt. To measure standing exercises and provide biofeedback, two motion sensors would be required. For example, one motion sensor would measure the movement of the upper leg and another would measure the stability of the spine or the ability to maintain "neutral spine". Supporting two motion sensors introduced major changes to how I approached the prototype. The serial interface emulation, provided by the LightBlue Bean library and used in the first prototype, did not support the use of multiple sensors (Figure 14). The Bluetooth protocol had to be accessed directly or using another strategy. Considering the importance of standing exercises to segmental stabilization, as evidenced by the interviews, I decided to build a new prototype with 2 motion sensors that would support such exercises.

5.2.2
Act

After the explorations with different sensors described in subsection 5.2.1 of this cycle and the insights gathered from the interviews with physical therapists, I began to prototype a StableBelt with 2 LightBlue Beans, which will be described in the following sections.

5.2.2.1 The JavaScript prototype

During the second cycle, a new prototype started to be developed using JavaScript, Node.js and Noble (a Node.js library that provides an higher abstraction level layer for Bluetooth support). This choice was based on available libraries that support the Bluetooth protocol directly and allowed for multiple motion sensors. Using Node.js required the Xcode environment and new version of the operating system. The audio biofeedback in the first prototype was based on the Minim audio library that came with the Processing language, version 2.0. The change to JavaScript required switching to Web Audio for generating the audio biofeedback.

5.2.2.2 Bluetooth and Noble

The use of multiple sensors required a more complex configuration of the communication components of the software (Figure 23).

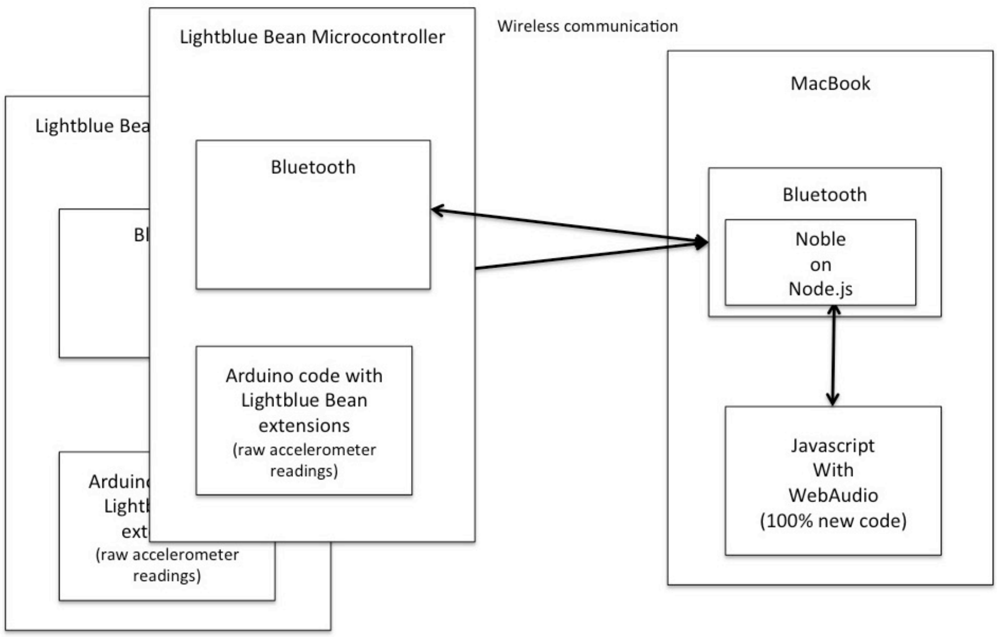
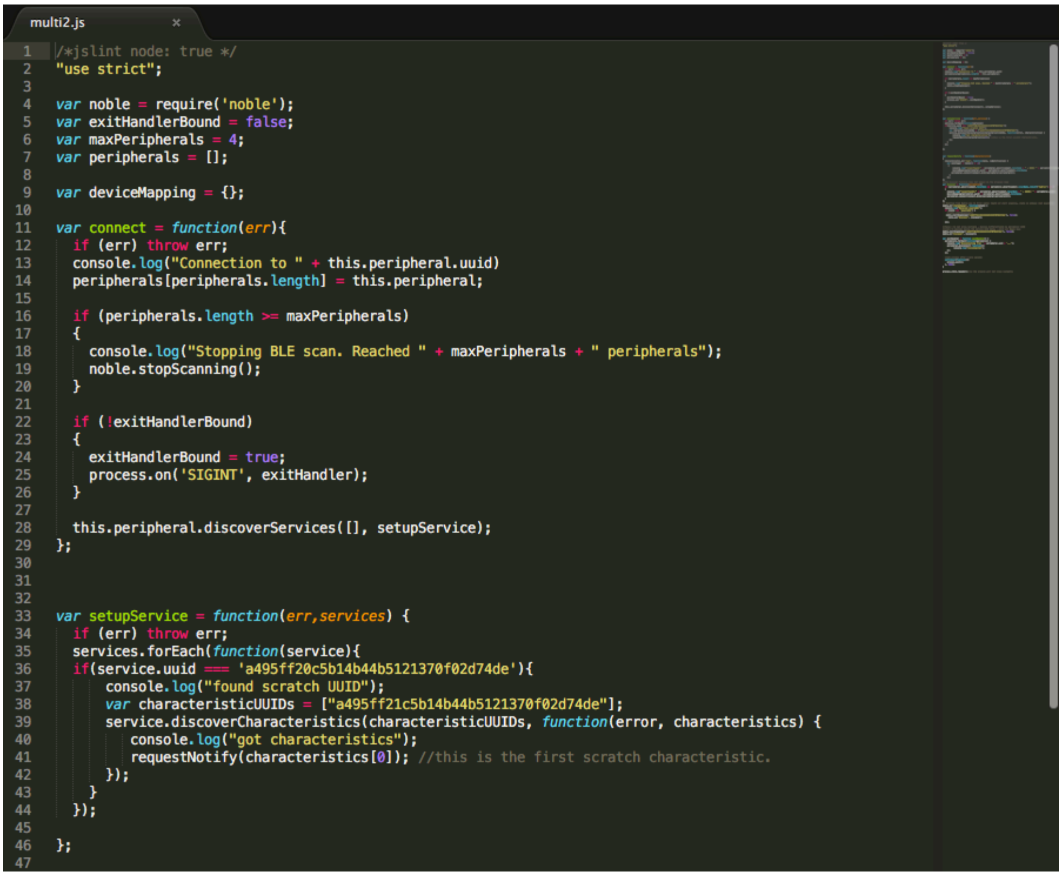


Figure 23 - Communication between multiple sensors and one computer

The open source code, I found, had errors and enabling it to run partially required considerable effort. To the best of my knowledge, it was the most similar open source code available to help implement the prototype with two LightBlue Bean's microcontrollers (Figure 24).



multi2.js

```
/*jslint node: true */
"use strict";

var noble = require('noble');
var exitHandlerBound = false;
var maxPeripherals = 4;
var peripherals = [];

var deviceMapping = {};

var connect = function(err){
  if (err) throw err;
  console.log("Connection to " + this.peripheral.uuid)
  peripherals[peripherals.length] = this.peripheral;

  if (peripherals.length >= maxPeripherals)
  {
    console.log("Stopping BLE scan. Reached " + maxPeripherals + " peripherals");
    noble.stopScanning();
  }

  if (!exitHandlerBound)
  {
    exitHandlerBound = true;
    process.on('SIGINT', exitHandler);
  }

  this.peripheral.discoverServices([], setupService);
};



var setupService = function(err,services) {
  if (err) throw err;
  services.forEach(function(service){
  if(service.uuid === 'a495ff20c5b14b44b5121370f02d74de'){
      console.log("found scratch UUID");
      var characteristicUUIDs = ["a495ff21c5b14b44b5121370f02d74de"];
      service.discoverCharacteristics(characteristicUUIDs, function(error, characteristics) {
         console.log("got characteristics");
         requestNotify(characteristics[0]); //this is the first scratch characteristic.
      });
    }
  });

};
```

Figure 24 – Node.js code to implement multiple sensors

5.2.2.3
Decision to discard prototyping effort

Three weeks were spent learning the skills for the new prototype and adapting sample code to handle multiple motion sensors. Due to the learning curve, the number of errors that were encountered, and the difficulty in assessing an estimated date for having a functioning prototype, a decision was made to end this cycle without completing the prototype with 2 motion sensors and without conducting a user test.

5.2.3 Observe

Since there was no functioning prototype for this cycle, no user tests were conducted and no data was collected for the second cycle.

5.2.4 Reflect

The challenges encountered while developing the prototype for 2 motion sensors and the decision to discard this strategy caused succeeding efforts to focus on a single motion sensor and use the code started in the first cycle targeting the SB exercise. The next cycle describes the effort to improve the audio biofeedback by making the sounds for correct and incorrect alignment more distinct.

5.3 Third Cycle – Piano and Drums

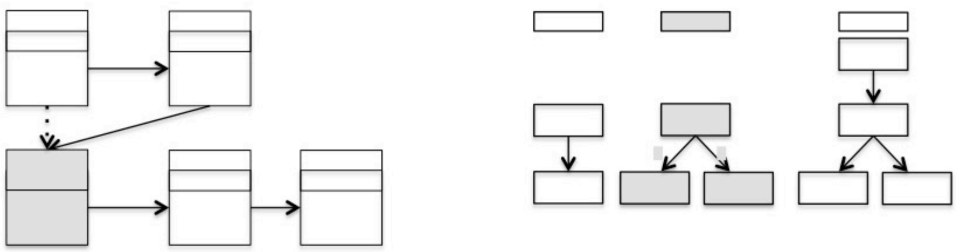


Figure 25 – The third cycle in context

In this cycle, two timbres were added to the audio biofeedback and a user test, with 5 participants, was conducted.

5.3.1 Plan

When resuming my work with a single motion sensor and the Bridge exercise, my efforts were directed towards the sounds generated for the audio biofeedback. After some experimentation with open source code for creating different types of sounds, I decided to implement an audio biofeedback based on two timbres: 1. A simulation of a piano key played at 440hz (La), while participant was within boundaries of correct alignment; 2. A simulation of a drum beat the correct position, while being outside the boundaries of correct alignment. The drum beat increased in frequency as the participant approached the position of correct alignment. Another possible configuration would be to have the frequency decrease as the participant approach the desired position. This configuration and its consequences will be discussed in sub-section 5.4.4 – Reflect of the next cycle, where more comments regarding this configuration were captured.

The rationale for this strategy was that it would be easier to perceive the incorrect alignment with a distinct boundary in the audio, with a change timbre, as compared to a more subtle variation in the audio level of the instrumental acoustic guitar music, as the audio biofeedback in the first cycle. The complexity of music perception had been raised as a complicating factor by Professor Clarisse de Souza, during the project proposal.

The choice of a simulation of a piano key as opposed to a continuous tone was a consequence of the explorations with continuous tone during the first cycle of this research. Many experiments with audio biofeedback use a continuous A440 tone (Dozza, et al., 2011). They are usually setup as negative feedback, such as, louder means more incorrect positioning or off balance. As I mentioned in subsection 5.1.1.4 of the first cycle, according to my experience, this should not be used for positive feedback. For example, maintaining the A440 continuous tone at a medium to high loudness while the user is in correct alignment, to avoid potential discomfort.

5.3.2
Act

To investigate the 2 new timbres for the Audio Biofeedback, I added piano simulation code and drum simulation code to the prototype and conducted a test, with 5 participants.

5.3.2.1
The third prototype

A new prototype was developed using the first prototype as a base and adding modifications of open source code for a piano simulation and a drum beat simulation, which were found on the Internet. These two simulations were written in the Processing language, based on the Minim audio library. An overview of the Processing code modules can be seen in Figure 26.

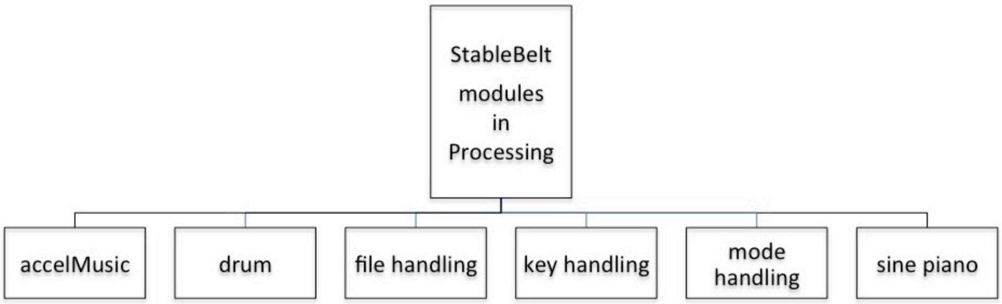


Figure 26 – StableBelt code modules in Processing

The open source code for the drum simulation was found in the Open Processing site (http://www.openprocessing.org, accessed on: Jan 23, 2016). The project was called DrumSound (http://www.openprocessing.org/sketch/62120, accessed on: Jan 23, 2016). A fragment of the code for the drum simulation appears in Figure 27.

```
accelMusic | drum | file_handling | key_handling | max_min | mode_handling | sinePiano | timing
      imp[i][j]=0;
      // translate by a velocity
      amp[i][j]+=vel[i][j];
      // sum the amplitudes of the drum
      val+=amp[i][j];
    }
  }
  // normalize to an average amplitude
  val /= sq(drumSize);
  // clip audio
  return constrain(val,-1,1);
}
class drum implements AudioSignal{
  void generate(float[] samp){
    // You may not make changes in
    // the data outside of this routine.
   // when mode=1 and biofeedback=false should turn bng off or return
   if ((mode == 1) && (biofeedback ==false)) bng=false;

    if(bng){
      bng=false;
      // get a random point on the drum
      //int a=floor(random(1,drumSize-1.001));
      //int b=floor(random(1,drumSize-1.001));
      int a=9; int b=9;
      if (!above)  {
       a=2; // find best drum beat
       b=2; //fix point on the drum
      } else {
       a=9; // find best drum beat
       b=9;
      }
      // deliver a big impulse
      amp[a][b]=bngImp;
    }
    for(int i=0;i<samp.length;i++){
      // get an amplitude while updating the simulation
      samp[i]=update();
    }
  }
  void generate(float[] left, float[] right){
    // this is a mono drum
    // this routine returns a zero signal
  }
}
```

Figure 27 – Code to handle drum simulation

```
accelMusic | drum | file_handling | key_handling | max_min | mode_handling | sinePiano | timing
class MyNote implements AudioSignal
{
     private float freq;
     private float level;
     private float alph;
     private SineWave sine;

     MyNote(float pitch, float amplitude)
     {
         freq = pitch;
         level = amplitude;
         sine = new SineWave(freq, level, out2.sampleRate());
         // ***** EXPERIMENT WITH THE LINES BELOW (FCI)
         alph = 0.975;  // Decay constant for the envelope ***** Experiment with decay
         out2.addSignal(this); // How many can we have?
     }

     void updateLevel()
     {
       if (correct == false) {
          out2.removeSignal(this);
          return;
       }
         // Called once per buffer to decay the amplitude away
         level = level * alph;
         sine.setAmp(level);

         // This also handles stopping this oscillator when its level is very low.
         if (level < 0.01) {
             out2.removeSignal(this);
         }
         // this will lead to destruction of the object, since the only active
         // reference to it is from the LineOut
     }

     void generate(float [] samp)
     {
         // generate the next buffer's worth of sinusoid
         sine.generate(samp);
         // decay the amplitude a little bit more
         updateLevel();
     }

    // AudioSignal requires both mono and stereo generate functions
    void generate(float [] sampL, float [] sampR)
    {
        sine.generate(sampL, sampR);
        updateLevel();
    }
}
```

Figure 28 – Code for piano simulation

The open source code for the piano simulation was found in the Open Processing site (www.openprocessing.org, accessed on: Jan 23, 2016). The project was called Keyboard Piano (http://www.openprocessing.org/sketch/99584, accessed on: Jan 23, 2016). The original code was developed by Neel Virdy and Annie Chu. A fragment of the code that implements the piano simulation appears in Figure 28.

5.3.2.2
The second user test

Five male volunteers (ages: 23-39 yrs., heights: 165-188 cm) used the third prototype. The participants were not suffering from low back pain, as was appropriate for this test. Participants were briefed and signed an informed consent form. This form was approved by the university ethics committee and the complete research protocol is included in Appendix C – Research Protocol (in Portuguese). The participant would place the belt, with motion sensor, around his waist and I would help adjust the position of the sensor, if necessary.

Next, each participant executed the SB exercise three times without ABF, while being manually guided for correct alignment, respecting any restrictions due to discomfort or pain. These initial repetitions were used to collect data for calibration. I calculated a mean of the Y-axis for the three trials, using Microsoft Excel. This value was used as the goal for the ideal position to be maintained during the repetitions of the exercises. This task was streamlined for the third test, requiring a single command and only 3 seconds of data to establish the goal value.

After establishing the goal value, the participant executed the SB exercise 6 times, being guided verbally when: to raise the hips, to maintain position, to lower hips, and to rest. He was instructed not to expect ABF during the last 3 repetitions. At the end of the 6 repetitions, the participant would sit and remove the belt.

In this cycle, a separate execution of the program had to be started manually for each execution and another command to start data collection, when I identified that participant had reached the correct alignment. The presence of audio biofeedback was also a parameter that had to be manually modified in the source code prior to the execution of the third repetition. This manual steps and counting required extra attention and could be a source of errors.

Each session would end with a semi-structured interview using the questions first 6 questions listed in Appendix A – Semi-structured interview (in Portuguese).

5.3.3 Observe

Following the structure of the first cycle, during each repetition of the SB exercise, a log was written in comma-separated format (CSV). Each log contained header information with date and time of when the log started, whether audio biofeedback was present, the goal and margin used to calculate the audio biofeedback, the accelerometer axis measured to generate the audio biofeedback and accelerometer data with labels when the period of 22 seconds started and ended, an additional column registered what loudness was calculated for each reading. For the SB exercise and the orientation of the motion sensor relative to the spine, the Y-axis was always used. These values are compared to the goal and margin values listed in the header section at the beginning of the log. These logs were reviewed using Microsoft Excel in the following days and graphs were generated in R (Figure 29).

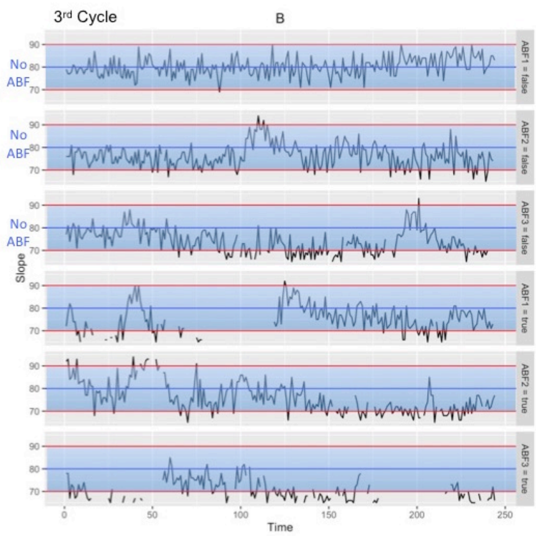


Figure 29 – Sample graphs of data from third cycle. Top graphs represent exercise repetitions without Audio Biofeedback. Lower three graphs represent exercise repetitions with Audio Biofeedback.

Graphs representing the raw data gathered from the accelerometer during the third cycle and fourth cycles appear in Appendix B – Graphs from User Tests.

Reviewing graphs from this test, a few patterns can be identified. All participants seemed to have close to perfect execution of the exercise during the last 3 repetitions of the exercise, when Audio Biofeedback was silent. During the first 3 repetitions, when participants received Audio Biofeedback, errors varied greatly in size, frequency and duration. The second repletion of the exercise with Audio Biofeedback seemed to have the least errors. No other trends could be identified.

A semi-structured interview followed each session in order to capture information about the experience of using the StableBelt. The interviews were based on the first 6 questions listed in Appendix A – Semi-structured Interview (in Portuguese); the remaining questions were only relevant to the fourth cycle.

5.3.4 Reflect

This section discusses data gathered in the Observe phase of this cycle. It starts by discussing the interview comments. Then, discusses how a particular interruption affected one of the test sessions and raised some issues. Lastly, it organizes possible directions for the next cycle.

5.3.4.1 Discussion of Interview Comments

Unfortunately, an accident happened before I could transcribe the participant's comments that caused audio recordings from the 5 interviews to be deleted and only the comments that I was able to write down were kept. Four participants from this test also participated in the test for the next cycle and some of their comments during the fourth cycle were in relation to this test, which allowed me to infer some information lost in the missing audio recordings. The comments in this discussion were transcribed using what was written down during the interviews and translated from Portuguese to English,

Some participants had difficulty understanding the ABF. Alternatives to the current audio characteristics of the ABF should be explored.

Participant B -- “Confused with sound. Not sure if should go up or down. If correct position was really.”
Participant E -- “Sound for down. Regulate the strength. A bit confusing”

One participant noticed that sometimes the two types of sounds would play at the same time.

Participant B -- “A bit lost … at the same time played two sounds, correct and incorrect.”

Some participants suggested changes to the ABF.

Participant B -- “Differentiate between go up and go down.”
Participant A -- “Timbre. Something more relevant (than) hollow sound (percussion)”
Participant E -- “Sound for up. Maybe a bit more different”
Participant A -- “Needs to finishing touches … sound more relevant.”
Participant D -- “It was good. Sound (could be) more clear. Possibly verbal. Sounds very close.”
Participant D -- “Verbal (feedback) could be nice.”

Some participants did understand the ABF. This suggests simple modifications to the ABF may suffice.

Participant E -- “Yes. It became easier (as I went along). No pain.”
Participant A -- “When was weak … left position and perceived the mistake.”
Participant C -- “Yes. No problem”
Participant C -- “It’s easy.”

Two participants spontaneously stated the belt was uncomfortable.

Participant C -- “Uncomfortable position (of device) on low back.”
Participant C -- “ Uncomfortable”
Participant D -- “Lying down hurts the back.”

One participant suggested how to improve the comfort. One consideration is the circuits are highly integrated and tampering with them may ruin the components.

Participant D -- “ Make it thinner. Undo the circuit and pull (battery) to the side.”

One participant asked for tighter fit in the belt. This can be addressed together with other belt design issues. This particular aspect was partially solved within this cycle by adding extra velcro.

Participant B -- "More firm. When you lie down, can become loose"

There were various positive comments regarding the StableBelt and the experience. This was encouraging and suggests the overall approach to the StableBelt has potential and should be further investigated.

Participant B -- "Feedback was quick. Responded according to movement"
Participant E -- "Comfortable. A good exercise. Orientation by sound"
Participant A -- "Good reference for the exercise. Abdominal (exercises) would be interesting."
Participant C -- " Feedback for correct position"
Participant C -- "Very simple."

One participant suggested the StableBelt support other exercises and elimination of the calibration step. This is more evidence that participants would like to see this approach to core stabilization exercises expanded.

Participant A -- "More positions. The device calibrates itself."

One participant felt positive about having the test encourage him to exercise, when asked what he liked about the StableBelt. His comments inspires reflection on how can we leverage social aspects of motivation in the design of the StableBelt.

Participant D -- " Make me do it."

One of the original goals for the StableBelt was to assist the patient in performing the exercises without supervision, as when performing the exercises at home alone. This scenario became the focus of the next cycle.

Since some participants in the third cycle test related having difficulty hearing the difference between the La note from the piano simulation and the drum beats, in the prototype for this cycle, more distinction should be explored between the two conditions in the next cycle. One possibility would be to play 3 different piano notes in repeating sequence (Do-Re-Mi) instead of A440 (La).

A problem was identified in the audio biofeedback at the moment the user exited the region of correct alignment. For a fraction of a second, he would hear both the drum beat together with the remainder of the last piano note. This could cause confusion and was addressed in the next cycle. In a real piano, this reverberation would be harder to silence. However, in this digital simulation, it is possible to abruptly silence the piano note.

The noise inherent in the accelerometer could also cause artificial errors when the participant was in the correct position and the sound of drums to appear inappropriately. This made me consider applying a filter to the data. Depending on the application, data from accelerometers is filtered by diverse methods from low-pass filters to Kalman filters. In the fourth cycle, I applied a low-pass filter (Krumm, 2009, 358) by calculating a moving average of the last three accelerometer readings at each line of data was retrieved. With the data transfer rate at approximately 10-12 Hz, this mean each read was the average of .25 seconds of data.

The drum beat increased in tempo as the participant approached the position of correct alignment. Another possible configuration would be to have the frequency decrease as the participant approach the desired position. This configuration and its consequences will be discussed together with the results of the next cycle, in subsection 5.4.4 – Reflect.

5.3.4.2
Distraction during test

During the test, one participant was performing the SB exercise when one of his friends entered the room. The participant’s attention was divided between the audio biofeedback and the comments from his the friend. This brought an element of reality that could be present in a clinic. Some issues were raised from this event: How well would the audio biofeedback work in a room with multiple patients? Would headphones suffice maintain the user’s primary focus on the audio biofeedback during the exercises?

5.3.4.3
Directions for next cycle

Given the knowledge acquired up to this point, some alternative directions for a next cycle are reasonable to consider. The difficulty some participants had in distinguishing the different aspects of the ABF, suggest some options for the audio characteristics could be explored. One way to make this distinction would be to add different notes to the piano component of the ABF, selecting based on the pitch distance to the drumbeats. Second, the percussion component of the ABF could be explored in order to differentiate more from the piano component. Third direction would be to work on the comfort of the belt, exploring different designs. This last direction was pursued in the fifth cycle.

5.4
Fourth Cycle – Unsupervised prototype

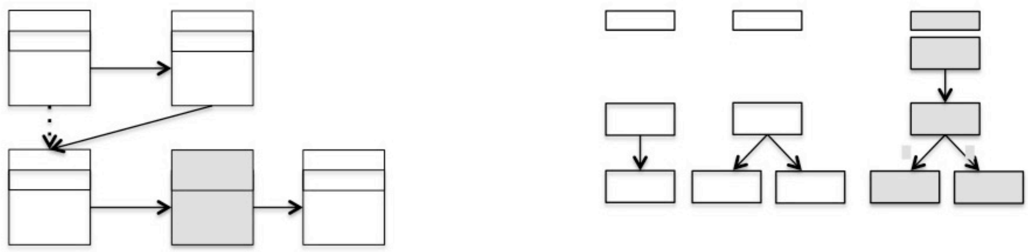


Figure 30 - The fourth cycle in context

The fourth cycle was dedicated to developing the prototype to the point where I could implement the scenario of the patient taking the StableBelt home and using it without supervision. For this to happen verbal commands were recorded and a method for triggering them at the correct time was devised. The new prototype was tested with 8 participants.

5.4.1
Plan

The focus of the fourth cycle was to have the StableBelt working without the presence of a physical therapist, after initial training and calibration. The strategy adopted to enable the StableBelt to support this scenario was to identify the verbal commands used during the execution of the SB exercise, record these command separately and play them at appropriate times, guiding the participant through different steps and informing when to rest.

In addition, I noticed the audio biofeedback immediately after leaving the margin of correct alignment was ambiguous. I needed to silence the piano keys whenever the drum beat started.

Since some participants in the third cycle test commented having difficulty hearing the difference between the La note from the piano simulation and the drum beats, in the prototype for this cycle, 3 different piano notes were played in repeating sequence (Do-Re-Mi) instead of A440 (La). Besides making the audio between correct and incorrect position more distinct, the three notes also had the potential benefit of improving the aesthetic experience of the participant while performing the exercise correctly.

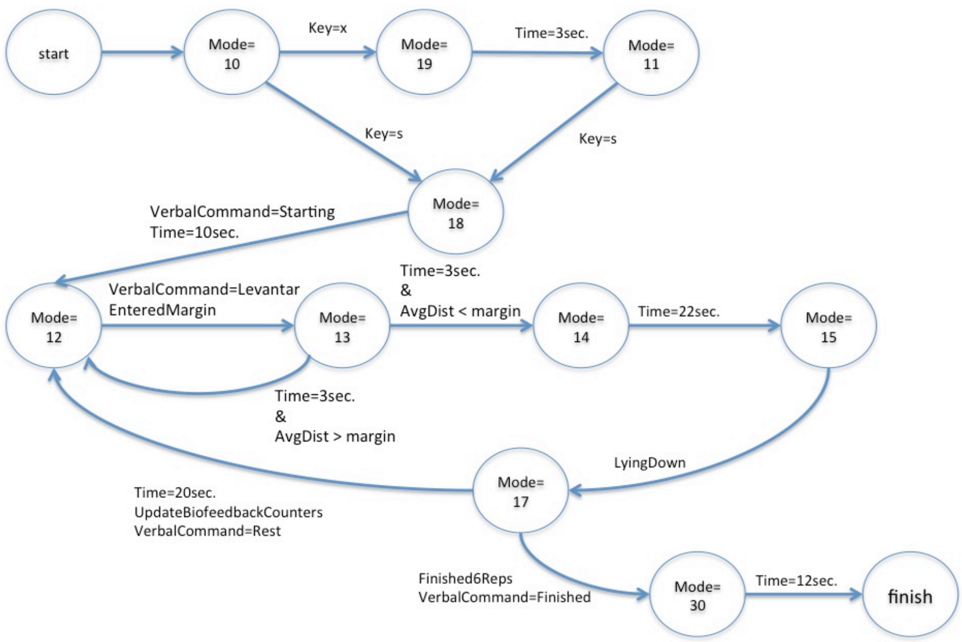


Figure 31 - State-transition model to generate verbal commands

An elaborate state transition model was conceived to support the full automation of the verbal commands and the functioning of the prototype without manual intervention from a physical therapist. The verbal commands that guided the participants were associated with the transition between internal states (**Figure 31**). It would be interesting to adapt this model to other exercises, such as, other variations of the Bridge (e.g., Single-legged Supine Bridge) or variations of Quadruped exercise. One possible evolution would be to start with those exercises whose verbal commands follow similar sequence and trigger conditions, then transition to exercises with even more elaborate flows.

5.4.2 Act

Much of the coding effort in this cycle went into triggering the correct verbal commands in a smooth flow that would not get in the way of the participant executing the SB exercise or leave him wondering what to do next. All participants were able to complete the exercises without supervision, as evidenced by the logs and videos recorded.

5.4.2.1 The fourth prototype

The prototype used in the third cycle was enhanced to implement the state transition model (Figure 32). This implementation would trigger the verbal commands at the appropriate times. Some of the triggers were based on position of the body, some were based on time constraints, and some were a combination of position and time. The prototype kept counters for the number of repetitions with and without audio biofeedback during the 22 seconds that user maintained position. The participant always received audio biofeedback, when he was instructed to raise the hips towards the SB position.

```
//entered margin
void setMode13() {
  background(0,0,250);
  mode=13;
  resetStartTime();
  resetAvg();
  writeModeSeparator();
}

void testMode13(int elapsed) {
  int tmpDist = 0;
  int testGoal = int(runningAvgSensors[gainSensor]);
  tmpDist = testGoal - goal;

  if (tmpDist <= margin) {
    setMode14(elapsed); // start the exercise
  } else {
      background(100,200,100);
      mode = 12;              // unable to establish position, try for another establishTime
      resetStartTime();       // Should restart from scratch?
      resetAvg();
      writeModeSeparator();

  }
}
void setMode14(int elapsed) {
  background(0);
  mode=14;
  resetStartTime();
  resetAvg();
  writeModeSeparator();
    text("Maintain Position" , (barX + (4 * 1 * barWidth) - barWidth), 40);

  if ( biofeedback == true) playCommand(1); // hold for 20 seconds
  else playCommand(5); // mention to hold in silence

}

// just finished 22 seconds of automated exercise
void setMode15(int elapsed){
    background(200,200,220);
    mode=15;
    writeLogSummary22(elapsed);
    resetStartTime();
    nextSong();
    correct = false;
    textAlign(LEFT);
    //text("FINISHED Mode 14 - Lowering ", 10, 40, -200); //why -200?
    text("Lower hips " , (barX + (4 * 1 * barWidth) - barWidth), 40);
    playCommand(2); // lower hips
}
```

Figure 32 - Sample code to implement state-transition model

The low-pass filter was implemented by calculating the average of the last 3 accelerometer readings at each new line of data retrieved. The sound of the piano key was silenced immediately prior to playing the first drum beat indicating the participant left the boundaries of correct alignment.

5.4.2.2
The third test

Eight volunteers (4 males and 4 females, height: 150-188 cm, age: 26-39 yrs.) participated in the test. All participants were not suffering from low back pain at the time of the test. Participants were briefed and signed an informed consent form. This form was approved by the university ethics committee and the complete research protocol is included in Appendix C – Research Protocol (in Portuguese). The participant would place the belt, with the sensor, around his waist and I would help adjust the position of the sensor, if necessary.

To set the goal value, I would guide the participant to the correct alignment, issued a keyboard command on the laptop computer that would calculate the average value of the Y-axis for 3 seconds of accelerometer readings, this goal value would be stored in the program and used during the 6 SB exercise repetitions to follow. I would inform the patient that I was leaving the room and issue another keyboard command that would start the sequence of automated verbal commands, which would narrated the repetitions of the exercise. At the end, the participant would be informed, he completed the exercises and could remove the belt.

After the exercises, a semi-structured interview was conducted using the questions in Appendix A – Semi-structured Interview.

Each session was recorded on video.

5.4.3 Observe

Accelerometer data was collected during the each exercise and log files were written with the same structure as the logs from the third cycle. Semi-structured interviews were performed after each session, using the questions listed in Appendix A - Semi-structured interview (in Portuguese).

Figure 33 shows an example of graphs that were generated for each participant in the fourth cycle together with the graphs for the same participant from third cycle test, for comparison. The other graphs appear in Appendix B – Graphs from User Tests. From this graph, we can see this participant had very few moments where his alignment was incorrect during the 22 seconds of the SB exercise.

All participants were recorded on video.

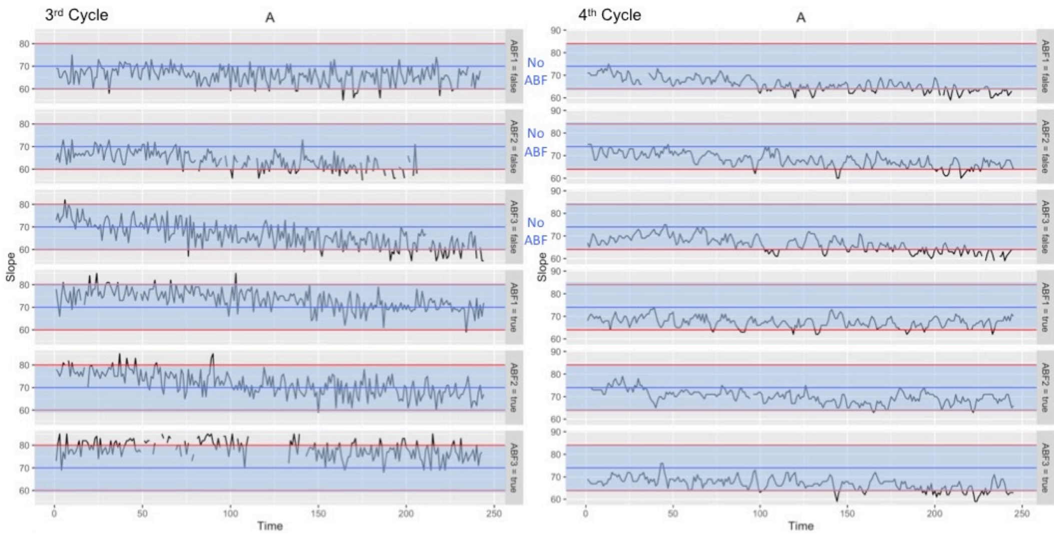


Figure 33 – Sample graphs from third and fourth cycle tests for a participant. Upper 3 graphs represent repetitions without ABF. Lower 3 graphs represent repetitions with ABF.

Although one may be tempted to make an analysis of data across cycles and participants, there are several reasons that cause the comparison of data between participants and between tests to be inappropriate. The next section describes these reasons.

5.4.3.1
Data Comparability across cycles

Changes in the characteristics of user tests between the action research cycles make certain quantitative comparisons inappropriate. At least six types of changes can be identified: participants, experience, quality of intervention, autonomy, automation, and context. The number of participants increased from 1 participant in the first test to 5 in the second test and to 8 in the third test. While second test had 5 males, this ratio became more balanced with 4 males and 4 females in the third test.

The experience with the SB exercise varied for the participants who were returning after participating in the previous test. They were familiar with the procedures and quickly adapted to what was new in the third test. All participants who were in both tests reflected their memory of the previous test in their comments during semi-structured interviews. Table 1 shows the intervals between tests for each of these participants, as well as, the dates the particular sessions occurred.

3rd cycle participants (date of session)	4th cycle participants (date of session)	Interval between sessions (days)
A (10/23)	A (11/10)	18
B (10/20)	B (11/03)	14
C (10/23)	C (11/05)	13
D (10/27)	D (11/05)	9
E (10/22)	n/a	n/a
n/a	F (11/05)	n/a
n/a	G (11/09)	n/a
n/a	H (11/10)	n/a
n/a	I (11/12)	n/a

Table 1 - Dates of test sessions for each participant and interval between sessions

The quality of my intervention improved as I gained confidence in the procedures, with practice. I sensed that each new session was more fluid. During the third test, my intervention was minimal. I would brief the participants, provide initial training, position the participant and issue the command to calculate the goal value (which lasted 3 seconds), and leave the room. These procedures were streamlined with much smaller opportunity for error. The training also improved and covered more details, which were consequence of the knowledge acquired with each additional participant's session. In the third test, when I left the room, after the briefing and training, there was silence with the exception of the recorded verbal commands and the ABF. Hence, my intervention was very small during the sessions of the third test. The verbal commands were recorded while I was alone and calm. Each recording was the best one, selected from a few attempts.

The level of autonomy of the participants was increased in the third test. They did not require my presence while performing the 6 repetitions of the SB exercise and could advance to the next verbal command by clicking on the mouse. Participants started being recorded on video during the third test. Having the camera in the room and being aware they were being filmed could make the participants more conscious of themselves and affect performance, depending on how they felt about being filmed while performing exercises. Some participants, may pay more attention to the their bodies and to the feedback, in order not to make mistakes in front of the camera. Other participants could be more nervous and more error prone. Some participants may completely forget they were being filmed and focus solely on the task at hand. After reviewing the video tapes, the last scenario appears to be the case for most of the participants.

The prototype used in the third test included features that potentially affected performance relative to the ABF. It had homogeneous verbal commands and precise duration for the rest periods. The potential ambiguity in the ABF when crossing the margin to the incorrect position was eliminated. Artificial errors resulting from the accelerometer's noise were decreased due to the low pass filter, implemented in the fourth cycle.

The context for the third test changed in two aspects. Participants lied down on a yoga mat instead of instead of being in direct contact with the surface of the table, which was more firm and less comfortable. The third test happened later in the semester. Since most participants were also students at the university, they may have been dealing with finals and deadlines and have less time in general. This could cause participants to approach the test with a desire to finish in less time. On the other hand, the test was more structured and streamlined in the third test and tended to take less time than the second, for those participants who participated in both.

Due to the small interval between sessions for the participants (Table 1), most repeating participants made comments relating to the previous experience. This implies they remembered the previous experience and were conscious of differences and similarities. This has a positive and a negative impact. For the prototype changes, I was able to get their impressions on what the modifications felt like, which was very useful. On the negative side, their impressions were affected by their experience in the previous cycle and they did not respond as if encountering the StableBelt for the first time.

5.4.3.2
Data Comparability across participants

Participants presented many differences that could affect their performance and render comparisons across participants inappropriate. Participants had different level of physical conditioning and body weight. Some participants would experience fatigue quicker than others. Participants had different levels of interest in performing the exercise. A couple of participants volunteered comments regarding having had low back pain in the past, which would increase their interest in potential solutions, expecting their pain may return in the future. Their relation to audio varied. Some participants were more perceptive and could identify characteristics of the audio feedback that others could not. Some referred to the Do-Re-Mi sequence of notes as music. One participant spontaneously spoke of enjoying the sounds of the audio feedback and the music that was played during rest periods. Their attention, concentration and perception of the audio feedback could influence how the execute the exercise relative to the audio biofeedback.

5.4.3.3
Edited video

Each session was recorded on video. I edited a video with some representative scenes from the test and published it on YouTube: StableBelt – Wearable for core stability - https://youtu.be/lNs7HAvob7o, accessed on: Jan 23, 2016. A single frame from the edited video can be seen in Figure 34.

Figure 34 – A frame from the edited video of the fourth cycle test

5.4.4
Reflect

This section discusses data gathered in the Observe phase of this cycle. It starts by discussing the interview comments. Second, organizes suggestions for ABF. Third, discusses the percussion aspects of the ABF. Fourth, discusses whether StableBelt is intended to assist of substitute the physical therapist. Lastly, lists possible directions for the next cycle.

5.4.4.1
Discussion of Interview Comments

In this section, I present the categories of comments that were identified in the transcripts from the semi-structured interviews conducted at the end of each participant's session. Comments were translated from Portuguese to English.

An interesting discovery during the 4^{th} cycle test was that for some participants the simple sequence of piano notes Do-Re-Mi was perceived as music. A simple change from a single La note to Do-Re-Mi sequence may have interesting consequences. Perceiving it as music suggests that it might be more pleasant. It should also provide more contrast with the percussion sounds.

Participant H classified both the Do-Re-Mi and the recorded guitar music played during the rest period as music, as if both belong to the same category.

> Participant B -- "Now is like music. When I am right is music. Not sure, seems like music"
> Participant H -- "I really like the music, during rest and during correct position"

Other comments also pointed to the preference of performing the exercises with ABF and how they missed the presence of the audio feedback during the repetitions when ABF was absent. Although, this is very encouraging, it has the downside of making users dependent on the ABF. This dependency has to be evaluated whether it fits as a long-term goal. In case dependency is not desired, strategies must be put in place to minimize this aspect over time. These comments may reflect the novelty of the experience.

> Participant B -- " I felt orphan without the sound."
> Participant F -- " I would prefer if the 6 (repetitions) were with sound. The last 3 without sound, I didn't know if I was correct or incorrect."

One participant commented she enjoyed being corrected by the ABF. Another comment reflected a positive attitude towards the ABF, indicating a perception of assistance from ABF.

It is not clear from the comment how she felt about the percussion sound.

> Participant G -- "I liked when it corrected me, when I was in the wrong posture"
> Participant B -- "(I) Felt like it helped."

In contrast to the participants who missed the ABF during the last three repetitions, one participant accepted as just another condition that required him to pay more attention.

> Participant C -- " … ok, they are the rules of the game … At most, I had to pay attention."

Participant H, who perceived the Do-Re-Mi sequence as music, also enjoyed the silent repetitions and how the test alternated between the two conditions. Perhaps, making the characteristics of each condition more noticeable by the contrast.

> Participant H -- " I liked the variation between one moment have music and the other moment not have (music)".

Two participants spontaneously spoke of the percussion in negative terms. One in reference to his own experience and the other spoke hypothetically how other people might receive the percussion sound.

Participant A -- "The negative (sound) 'tow', the 'punch' …"
Participant F -- "In truth, it could irritate … if it stays 'tum-tum-tum' …".

One comment, that can be viewed as suggestion aligned with the goals of the StableBelt, was the addition of verbal encouragement. This could be implemented with increasing degrees of complexity. From simple conditions that trigger pre-recorded verbal encouragement to more complex adaptive triggers that in some way account for how previous encouragements affected performance of the stabilization exercise. This suggestion also informs the discussion of whether the StableBelt is there to assist or substitute the physical therapist. This suggestion is further elaborated in the discussion on subsection 5.4.4.4 - Assist or substitute the physical therapist.

Participant A -- "The only thing missing was to put a commentary: 'Yes! That's it!' A reinforcement during the execution (of the exercise)".

Another suggestion was to make the sound for incorrect alignment drastically different. For example, using the sound of a siren. When asked how future users might perceive this configuration, he reasoned that it might be annoying. Nevertheless, it might be useful to reflect on possible ways to make the correct and incorrect sounds more distinct for the users that cannot easily differentiate the two types of audio biofeedback present in the prototype for the fourth cycle.

Participant D -- " (Incorrect sound) Could be the sound of a siren …"

One participant spontaneously stated that she enjoyed the lack of visual feedback, which allowed her to perform the exercises with her eyes closed. This was one of the motivating factors for choosing the auditory modality for the biofeedback. If other modalities were presented, participants may have offered more comments regarding this preference. In fact, this participant told a story about an exercise related software application she had previously tried on her tablet, which had a visual interface. She found having to look at the tablet while performing the exercises very annoying.

Participant H -- "I really liked. I did with eyes closed. I thought was really nice, it not being visual. Really like not having to look at a screen."

Some participants felt the belt was uncomfortable when lying down. The different anatomy between the participants allowed some to have just enough space between the spine and the table to be comfortable. For other participants, this space was not enough and the plastic case pressed against the spine. The discomfort using the belt had already been reported in the previous test.

Participant D -- “This time it was a bit more uncomfortable … I turned to the side.”
Participant C -- “I turned a bit.”
Participant F -- “The sensor was a bit uncomfortable (after the 3rd time) when I laid down.”
Participant G -- “(Belt) was not uncomfortable.”
Participant H -- “Found (belt) comfortable.”
Participant I -- “The belt was good.”
Participant A -- “Laying down was not uncomfortable”

Some comments suggested that participants still remembered their experience of the previous test and offered comparisons. One participant felt that it became easier. Since there were multiple changes between the prototypes used in each test, we cannot affirm how much each change contributed to this perception. For another participant, the change from La note to Do-Re-Mi was an improvement, as he compared the latter to music.

Participant B -- “Before the correct sound was also ‘pim-pim’. Now is like music”.
Participant C -- “ I felt it was easier (this time)”.

The rest periods could be shorter between the first repetitions but should be maintained between the last repetitions, suggesting this participant could be mildly fatigued as repetitions progressed.

Participant C -- “I would cut (rest periods) in the beginning, then I would not cut, in the end was just right”.

Some participants performed considerably better than others and at least on participant described his perception of success. Participant C had also mentioned the condition without ABF was reasonable to him. Interestingly, the logs for participant C do show perfect execution of the SB exercise with ABF and only one minor error when executing without ABF.

Participant C -- “ (Correct sound) This is what I experienced the whole time.”

The wide range of perceptions of the audio is partly evidenced by the distinct words (onomatopoeia) participants chose to describe what they heard. Sometimes using the same word to describe different sounds, which makes it unclear if they did not hear the distinction originally or used the same word for lack of a better method for description.

Participant A -- “The ‘tow’ …” (percussion)
Participant A -- “ The ‘tan-tan-tan’ of the positive …” (piano Do-Re-Mi)
Participant B -- “pim-pom, pim-pom” (piano-percussion in previous cycle)
Participant F -- “ … tum-tum-tum …” (percussion).
Participant F -- “ …toc-toc … “ (percussion)”

All the previous themes show the richness of perceptions and reactions even with a relatively small sample of participants. One possibility for continuing experimentation with the audio would be to vary the sequence of conditions with and without ABF.

5.4.4.2
Suggestions for Audio Feedback

If we analyze the data regarding the ABF, some patterns start to emerge. Some design suggestions for the audio biofeedback that can be derived from the these patterns:

- Make sounds distinct through different timbres. To be effective users need to quickly distinguish between sound of correct and sound of incorrect alignment. The difference in timbre between piano notes and percussion is an alternative the proved to be efficient in this preliminary investigation.

- Keep sound for correct alignment pleasant. The use of Do-Re-Mi notes in sequence was perceived as music by some participants. This provides some indication that users found it pleasant. The combination of pleasant continuous sound can add additional positive reinforcement during the practice of the exercise.

- Keep sounds simple. In order to make the ABF instantly recognizable and cause minimal cognitive overload, it is best to maintain simplicity. In contrast to the recorded acoustic guitar music presented in the first test, when the participant would take considerable time to react. The combination of pleasant continuous sound can add additional positive reinforcement during the practice of the exercise In this investigation, I used at most a sequence of 3 piano notes, with a slow tempo (1 second apart). The one particular percussion sound that varied in tempo to serve as warning.

- Sound for incorrect alignment needs to happen fast but not necessary in fast tempo. Participants were able to make quick correction based on the fast percussive sounds. The fast tempo may be annoying to more sensitive listeners.

Further testing is needed with other possible configurations. A slower tempo percussion may be played when user crosses the threshold of incorrect alignment and gets faster as user distances from the threshold. Another alternative to feedback errors would be to make it also piano notes from another octave (i.e. different pitch range), making sure to interrupt notes when crossing the threshold, so as not to confuse participant.

5.4.4.3
Configurations of Audio Feedback

Does the percussion sound that informs the participant of incorrect alignment need to be fast tempo when the participant crosses the threshold? Or can it just happen immediately with a slow tempo? Which direction should the tempo increase? These questions remain open after the user tests. Most participants reacted quickly to the audio feedback suggesting it does not need to be high frequency. It is likely the fast tempo percussion could be uncomfortable to many people. There are at least two related dimensions to this aspect of the audio feedback. One is the direction of the increase in tempo. The other is the range of tempo that the percussion sound covers. It is possible to make both of them configurable by the physical therapist or the user. The appropriate configuration will depend on the sensibility of the user, how well he performs the exercise and how likely he is to make mistakes. The last two aspects of the user will probably improve with practice over time. We need to understand how quickly the user reacts to the change in audio feedback. In other words, how responsive the user is. We need to know how many mistakes the user is making. To achieve the best results, different ranges of tempo can be explored in addition to setting the direction of tempo increase. How fast is fast or how slow is slow? According to the participant's sensibilities.

The perceived difference between the piano and percussion timbres is also an important factor. When the piano sounds changed from the La note to the Do-Re-Mi notes, the perceived difference increased according to some of the participants' comments. The level of attention is another factor that can influence this perception of the audio for the error condition. To some extent the contrast between pleasant timbre for correct positioning or execution and negative timbre for incorrect positioning or execution may be desirable as a motivational element, becoming an additional incentive to maintain focus and reasonable effort to perform correctly. To find the appropriate balance will require further research.

Langlois (2008) investigated how auditory warnings are perceived across cultures (Langlois, et al., 2008). This research used a controlled setting with different timbres and frequencies to subjects from different countries (France, Germany, Great Britain, Korea, Turkey, and USA). One of the findings from this research is that when associated with a fast tempo, the onset has an effect on urgency, but not when associated with a slow tempo. They also found effect of different acoustic parameters was similar across the different countries involved. This research was conducted in the automotive domain, which suggests this may be a domain to track for further research related to perception of auditory warnings and perception of urgency.

5.4.4.4
Assist or substitute the physical therapist

When watching the videos for the third test with the unsupervised prototype, which begin as I am about to leave the room, after I have already conducted training and have set the goal value for the SB exercise, the following question may arise. When observing the participants interacting with the StableBelt alone without human supervision, one may question whether the goal of the StableBelt is to assist or substitute the physical therapist. The short answer is: to assist the physical therapist. Part of the justification for this answer is in what happened just prior to the video being recorded. The training that takes place at the start of the session and enables the rest of the session to happen smoothly, requires human-human dialog and is something that is not intended to be handled by the StableBelt system. This is one area where the expertise of the physical therapist is required. In addition to describing the exercise, using a combination of demonstration and guidance that he feels is most appropriate. By assessing a participant’s reactions and expressions of understanding, he may try different ways of explaining the exercise and other characteristics of the exercises. He may answer questions that arise, according to his previous experience and understanding of the goals of the exercises. He can explain how the StableBelt and ABF work. In addition, setting the goal value is a combination of visual assessment of correct alignment together with another dialog with the participant to ensure the position being held is not uncomfortable. Both initial training and setting the goal, could be attempted without human participation by resorting to state of the art computer vision techniques, as well as, speech recognition and synthesis. However, I suspect this combined approach would fall short of the interaction with a human physical therapist. Besides the cost-benefit considerations, the deeper issue remains to define which tasks, in this narrow domain, are adequately handled by the StableBelt and which tasks are better handled by a human physical therapist.

The tasks that are best handled by the StableBelt alone with the participant, possibly at home without supervision, are exactly those present in the videos. The repetition of an exercise, for which previous training has already occurred and for which guidance and corrections can be formally defined. These tasks are often repetitive by nature and may challenge the patience and attention of the physical therapist. As in the StableBelt prototype used in this fourth cycle, verbal commands can be recorded in ideal conditions and be delivered in a manner as to communicate patience and caring. In addition, the StableBelt could offer different options of virtual therapists to match a participant's taste for voice and personality In other words, the virtual therapist could be: male or female, more talkative or less talkative, more serious or more playful, use more technical language or more informal language.

This separation of responsibilities maximizes the inherent capabilities of the human physical therapist and the StableBelt. The physical therapist performs creative tasks that require rich experience, such as: diagnosing, initial training, and prescribing exercises. The StableBelt accompanies formally defined exercises, providing continuous feedback and verbal commands to guide the execution of the exercises. The tasks that might be considered the monotonous aspects of a physical therapist's job.

One possible enhancement, to the StableBelt would be to adopt a variation of the concepts present in the ELIZA system conceived by Prof. Weizenbaum in 60's, which continues to serve as inspiration to researchers today (Weizenbaum, 1976; Duggan, 2016; Beun, et al., 2016). In the StableBelt implementation, instead of text input the StableBelt would use motion sensor data to trigger timely verbal encouragement. This was partly suggested by participant A in one of his comments:

> Participant A -- "The only thing missing was to put a commentary: 'Yes! That's it!' A reinforcement during the execution (of the exercise)".

On a recent paper that discusses using concepts from Eliza, Duggan (2016) shows how applying psychological theory to the relationship between user and technology provides a way of understanding these human-computer interactions and thus improving the process of developing self-management technology (Duggan, 2016).

Another paper exploring unsupervised use of health technology, Beun (2016) implemented an automated e-coaching mobile system that used persuasive strategies improve adherence to self-help therapies without human interference (Beun, et al., 2016). The e-coaching system was developed for the domain of insomnia therapy, used natural language conversation and social strategies to improve motivation.

Another aspect of this separation of responsibilities is how to extend the system. I have described a modeling approach to guide the Supine Bridge exercise. Ideally, some of this modeling would be done by a physical therapist. To explore related issues, Huang (2015) has designed and evaluated an authoring tool for physical therapists, in his doctoral research at the HCI Institute of Carnegie Mellon University (Huang, 2015). His intentions align themselves well with my research:

> "Ultimately, the tool could be extended to act as an in-home coaching aide that would include not just instructions, but also encouragement, corrections if needed, and visualizations for the PT, customized to the PT's specifications. … The authoring tool prototype contains four main components: 1. A rule specification interface, with which the PT interacts to input the exercise specifications, 2. an exercise prescription database, where the specifications are saved, 3. a virtual assistant runtime environment, which loads and parses the specification file to generate the appropriate virtual assistant behavior during patient use, and 4. a patient interface where the corresponding visual and audio output is delivered to the patient."

His investigation was focused on physical therapy for hip and knee. His authoring tool was intended to allow physical therapists to use their own familiar anatomical language. The evaluation of the tool was conducted with 9 physical therapists.

5.4.4.5 Directions for next cycle

Given the knowledge acquired up to this point, some alternative directions for a next cycle are reasonable to consider. The next cycle could explore different options for the percussion sound. Modifying the tempo next to the threshold and the direction the percussion tempo increases (i.e. away from the threshold boundaries). Second, instead of percussion, another alternative to the incorrect sound could be piano notes with different pitch. A note with different duration from another octave relative the current Do-Re-Mi note sequence. Third, explore verbal encouragements triggered by specific conditions regarding the performance of the exercise. For example, a certain percentage of errors might trigger: “You can do better!” or “That’s it”. A fourth option would be to work on the physical design of the StableBelt focusing on improving the comfort for when participants are lying down against the table. This last option was the particular one chosen for the next cycle in order to take advantage of a workshop with designers and artisans for which I was selected to participate.

5.5 Fifth Cycle – New physical design

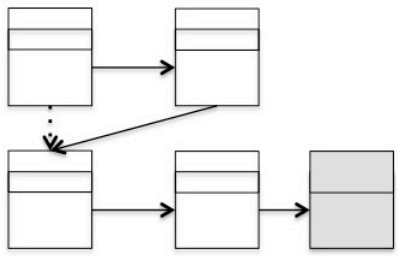


Figure 35 – The fifth cycle in context

The fifth cycle provided the opportunity to work on the physical design of the belt and to address complaints regarding the comfort of the StableBelt when pressing the back against the table. I went beyond the comfort requirement and investigated aesthetic issues taking advantage of the skills that were made available in a design workshop. This process will be described in the next section.

5.5.1 Plan

From the knowledge obtained in the previous cycles, I could proceed in at least two major directions: 1. Work to improve the ABF, possibly experimenting with sound variations for incorrect alignment; 2. Work to improve the physical design of the StableBelt. Given the opportunity to work with designers described below, I chose to pursue the second direction.

During this cycle, I was selected to participate in a design workshop at the Museum of Art of Rio de Janeiro (MAR), which allowed me to interact with: industrial designers, fashion designers, artists and artisans. After some physical prototyping, a new design was created and I proceeded to implement the belt in the next phase of this cycle.

5.5.2 Act

During the workshop a new design was conceived, using recycled neoprene (from a wetsuit), velcro, and pressure buttons. Due to a new extension piece, the new design allowed for greater adaptability. The thickness and softness of the neoprene material provided more protection for the LightBlue Bean, eliminating the need for the plastic case. It also addressed the aesthetics of the StableBelt, adding color and finishing touches. The black velcro is oriented across the belt as opposed to parallel to the length of the belt as in the original elastic band version. The pressure buttons allow for a strong connection between the main belt and the extension piece.

Figure 36 - The new StableBelt with extension part

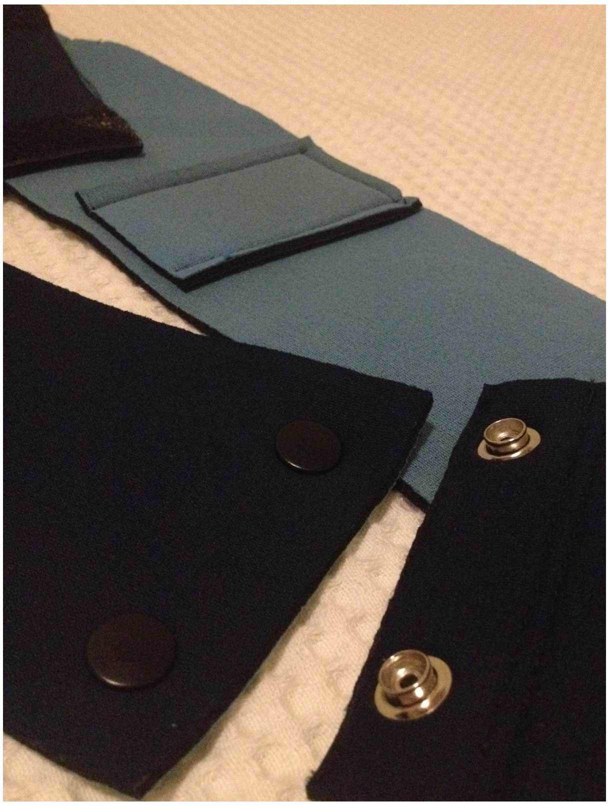


Figure 37 - Details of pressure buttons for extension part and pocket for microcontroller.

The second StableBelt design, with soft neoprene material, was conceived to allow the LightBlue Bean microcontroller to be used without the plastic case.

Since the microcontroller is much thinner than the plastic case, it should address the discomfort reported by some participants.

5.5.3 Observe

Since the physical aspect of the belt was not the primary focus of my investigation, I decided not to run a test assess the new belt design.

5.5.4 Reflect

The second StableBelt design, with soft neoprene material, was conceived to allow the LightBlue Bean microcontroller to be used without the plastic case. Since the microcontroller is considerably thinner than the plastic case used to hold it in the first design of the belt, it should address the discomfort reported by some participants.

The first two phases of this fifth cycle were completed at the end my last semester in the Master's program, leaving no time to complete another action research cycle. If I had more time, the next cycle should focus on options of the ABF, possibly sound alternatives for the incorrect alignment that were discussed in the fourth cycle.

6
Final discussion and conclusion

In this final chapter, I summarize the limitations of my research approach, my contributions, reflections from the five action research cycles, and highlight the milestones of the project. Future work, and further investigations on this topic, is also proposed.

6.1
Limitations

Given the sequence of repetitions**,** spontaneous motor learning could be influencing the results and favoring the silent repetitions that occur at the end of each test session (Dozza, 2011). We know that without extrinsic feedback (i.e. ABF), participants have to rely on intrinsic feedback and proprioception. Data from logs suggest that to maintain the SB exercise position, this internal sense is sufficient. When intrinsic feedback is combined with the potential spontaneous motor learning effect resulting from the sequence of repetitions, improvement in performance is likely to occur. Another limitation was the duration of the tests. If they occurred over days we could evaluate if retention and adaptation would take place.

As mentioned during the reflection phase of the first cycle, maximum loudness, did not receive adequate attention when ABF was based on recorded music. The lack of training prior to data collection implies participant did not have a clear target when listening to the music to reach the desired position.

Since no headphones were used, audio features such as panning or left-right balance could not be used. This would allow for another dimension. The use of speakers also allowed audio biofeedback to be heard together with other environmental sounds. As it happened, the room was fairly quiet most of the time, so few interruptions or distractions were present.

The use of the Minim audio library of Processing was useful because it integrated with the rest of the Processing code. The available open source code to simulate piano and to simulate drums were specially useful and made the prototyping effort very productive, while allowing manipulation of low level parameters, such as, the decay of the piano notes. When reviewing related work, I became aware that much research in sonification uses the software Max/MSP to generate the audio stream, especially when modifying acoustic features of a existing composition. In retrospect, this could allow more possibilities to modify the parameters of recorded music. Given my lack of experience with Max/MSP, it is not clear how my research would evolve using the Max/MSP software.

The SB exercise is likely not challenging enough for healthy participants to allow the potential benefits of the StableBelt to be noticed. However, the exercise was sufficient to show that users could understand the ABF and respond quickly, especially when using the 4th cycle version of the StableBelt.

6.2
Audio Biofeedback Considerations and Suggestions

The recorded instrumental guitar music used in the first test may have been too complex. The second test simplified the signal in order to achieve the desired perception between correct and incorrect alignment and also how far off the correct alignment. The third test introduced the three notes (Do-Re-Mi), which were received positively by all participants. Further explorations are necessary to investigate possible sounds for the error condition. Evidence suggests we are moving closer to achieving balance between three user requirements: understanding the audio biofeedback, recognizing errors, and having a pleasant experience. While many possibilities exist, these tests provide some evidence of a configuration that works until more alternatives are tested and achieve better results.

One could expect the absence of ABF to cause decrease in performance in the SB exercise, especially in the first repetition without ABF. The fact that this did not happen, suggests the SB exercise maybe too easy for this group and their proprioception is accurate enough.

Some design suggestions for the audio biofeedback that can be derived from the data collected during the 3 tests:

- Make sounds distinct through different timbres. To be effective users need to quickly distinguish between sound of correct and sound of incorrect alignment. The difference in timbre between piano notes and percussion is an alternative the proved to be efficient in this preliminary investigation.

- Keep sound for correct alignment pleasant. The use of Do-Re-Mi notes in sequence was perceived as music by some participants. This provides some indication that users found it pleasant.

- Keep sounds simple. In order to make the ABF instantly recognizable, it is best to maintain simplicity. In this investigation, I used at most a sequence of 3 piano notes, with a slow tempo (1 second apart). The one particular percussion sound that varied in tempo to serve as warning.

- Sound for incorrect alignment needs to happen fast but not necessary in fast tempo. Participants were able to make quick correction based on the fast percussive sounds. The fast tempo may be annoying to more sensitive listeners. Further testing is needed with other configurations. A slower tempo percussion may be played when user crosses the threshold of incorrect alignment and gets faster as user distances from the threshold. Another alternative to feedback errors would be to make it also piano notes from another octave (i.e. different pitch range), making sure to interrupt notes when crossing the threshold, so as not to confuse participant.

6.3
Assist or substitute the physical therapist

During the fourth cycle, the issue of whether the goal of the StableBelt is to assist or substitute the physical therapist in the long term. The short answer is: to assist the physical therapist. Part of the justification is the activities that take place at the beginning of each test session - training and setting goal value. The training that takes place at the start of the session and enables the remainder of the session to happen smoothly, requires human-human dialog and is something that is not intended to be handled by the StableBelt system. This is one area where the expertise of the physical therapist is required. In addition to describing the exercise, using a combination of demonstration and guidance that he feels is most appropriate. By assessing participant’s reactions and signs of understanding, he may try different ways of explaining the exercise and other characteristics of the **exercises.** He may answer questions that arise, according to his previous experience and understanding of the goals of the exercises. He can explain how the StableBelt and ABF work. In addition, setting the goal value is a combination of visual assessment of correct alignment together with a dialog with the participant to ensure that the position is not uncomfortable. Both initial training and setting the goal, could be attempted without human participation by resorting state of the art computer vision techniques, as well as, speech recognition and synthesis. However, I would expect this combined approach would fall short of the interaction with the human physical therapist. Besides, the cost-benefit considerations, the deeper issue remains to define which tasks are more adequately handled by the StableBelt and which tasks are better handled by a human physical therapist.

The tasks that are best handled by the StableBelt alone with the participant, possibly at home without supervision, are the ones for which guidance and corrections can be formally defined. The repetition of an exercise for which previous training has already occurred. These tasks are often repetitive tasks by nature and may challenge the patience and attention of the physical therapist. As in the StableBelt prototype used in the fourth cycle, verbal commands can be recorded in ideal conditions and be delivered in a manner as to communicate patience and caring. In addition, the StableBelt could offer different options for virtual physical therapists to match a participant's taste for voice and personality. In other words, the virtual therapist could be: male or female, more talkative or less talkative, more serious or more playful, use more technical language or more informal language.

This separation of responsibilities maximizes the inherent capabilities of the human physical therapist and the StableBelt. The physical therapist performs creative tasks that require rich experience, such as: diagnosing, initial training and prescribing exercises. The StableBelt accompanies formally defined exercises, providing continuous feedback, and verbal commands to guide the execution of the exercises. These tasks can often be the monotonous aspects of a physical therapist's job.

One enhancement, to the StableBelt, would be to adopt a variation of the concepts of the ELIZA system (Weizenbaum, 1976; Duggan 2016; Beun et al.

2016), where instead of text input, the StableBelt would use motion sensor data to trigger timely verbal encouragement. This was partly suggested by participant A, during the interview in the fourth cycle test, in one of his comments:

> Participant A -- “The only thing missing was to put a commentary: ‘Yes! That’s it!’ A reinforcement during the execution (of the exercise)”.

On a recent paper that discusses using concepts from Eliza, Duggan (2016) shows how applying psychological theory to the relationship between user and technology provides a way of understanding these human-computer interactions and thus improving the process of developing self-management technology.

Another paper exploring unsupervised use of health technology, Beun (2016) implemented an automated e-coaching mobile system that used persuasive strategies improve adherence to self-help therapies without human interference. The e-coaching system was developed for the domain of insomnia therapy, used natural language conversation and social strategies to improve motivation.

6.4
Benefits of music as audio feedback

Vast knowledge of music perception can inform the design of audio feedback for stabilization exercises. In my research, the simple sequence of Do-Re-Mi played by a piano simulation was considered by some participants as music. The percussive warning sounds of a drum simulation allowed for immediate recognition of error and corrective response. Music therapy provides many health benefits (Clair, et al., 2012). To have abstract sounds that can simultaneously provide precise real-time feedback on the performance of core stabilization exercises, and simultaneously, be perceived as music, could make the execution of these exercises more engaging and pleasant. In some ways, the adequate abstract sounds have the potential of being more efficient than verbal corrections issued by a physical therapist for very specific types of corrections, such as, position of the spine, during an exercise. Continued research on this topic could lead to a rich set of possibilities for rehabilitation of Non-specific Low Back Pain.

6.5 Conclusion

I am a physical therapist and a computer scientist researching in the area of Internet of Things and Wearables. While investigating potential uses of motion sensors for rehabilitation, I identified an opportunity for using these sensors to provide biofeedback to core stabilization exercises used in the treatment of low back pain. For this research, I selected the SB exercise, which is a common core stabilization exercise and easy to teach to test participants. Its structure gave me a well-defined procedure to measure stability.

My main contribution with this dissertation was a set of suggestions for designing Audio Biofeedback for systems that have similar characteristics as the StableBelt. In other words, systems that provides real-time feedback for maintaining correct alignment in part of the body (i.e. low back) during an stabilization exercise.

During the project proposal, some recommendations were made by Prof. Clarisse de Souza and Prof. Alberto Raposo. Prof. de Souza raised the issue that music perception is very complex and music might not serve as a good source for audio biofeedback. This motivated my experimentation with the simpler sounds of piano keys and drum beats. Prof. Raposo was concerned the project proposal was highly focused on the physical therapy aspects and less on Computer Science aspects. This concern caused me to shift my focus and look for opportunities to apply my computer science background. This is evidenced by the many prototype solutions, the implementation of automation of the verbal commands and the human-computer interaction aspects of the project, such as the user tests. Prof. de Souza commented on the importance of stating clearly my background as a physical therapist, which I believe I have done. My experience as a physical therapist combined with my knowledge of computer science made this research project possible.

Action research was chosen as a research method because it allowed me to conduct the research performing successive actions to attempt to reduce a specific problem in a real world environment (Herr and Anderson, 2005). The focus on actions in the world, observations and reflections was aligned with the needs of my research. In this dissertation, the environment chosen was a place where a patient executes exercises and the problem identified is the difficulty of the patient to perform the exercises correctly. The action was the introduction of a wearable – StableBelt – which generates audio biofeedback based on the patient's movements during a core stabilization exercise.

The action research consisted of five cycles. The first cycle served to get a base of prototype code running and to start to understand the details of running a test with this environment. I ran the test with one participant and identified the steps necessary to run a more complete test in a subsequent cycle. The audio biofeedback used in this cycle used recorded instrumental guitar music that lowered its loudness to indicate incorrect alignment during the SB exercise. The data for the first test suggested that audio biofeedback caused more movement. The data may also point to the fact that the perception of loudness of instrumental guitar music may be too imprecise, making this strategy not a reliable source of audio biofeedback.

In the second cycle, I attempted to support multiple sensors. Initially, exploring different additional sensors such as flex sensors and FSR sensors, which could potentially be used to identify neutral position of the spine, abdominal hollowing or palpation. Some breadboard prototypes were created and also "paper" prototypes. Later in this cycle, I attempted to prototype support for two motion sensors sending data simultaneously to the computer. The learning and coding challenges that I encountered made it unlikely that I would have the prototype complete in time to run user tests and I decided to discontinue this effort.

In the third cycle, I went back to using the prototype code started in the first cycle. I changed the audio biofeedback from recorded instrumental music to a simpler combination of two different timbres. The sound of a piano key when the participant was in correct alignment and drum beats that varied in tempo when alignment was incorrect. The data collected during this cycle suggested that participants could recognize quickly their errors and make necessary adjustments. The difference is stability between the repetitions with ABF and without ABF seem to be smaller than the first test.

In the fourth cycle, additional code was added to the prototype to allow participant to perform the exercises without supervision other than initial training and calibration. Code was also added to filter the accelerometer data prior to generating the audio biofeedback. Verbal commands were recorded and triggered at appropriate times to guide the participant. All tests were recorded in video. The data from the interviews and logs uncovered a number of trends, such as: three piano notes (Do-Re-Mi) could be perceived as music; participants could distinguish better correct from incorrect, participants found this version easier, the belt was uncomfortable. One participant suggested verbal encouragement be added to the ABF.

The fifth cycle focused on the physical aspect of the StableBelt and addressed the comments offered by some participants that when resting on the table, the plastic case that held the LightBlue Bean microcontroller, would press against the spine and caused discomfort. A new design for the belt was conceived during a design workshop that used recycled neoprene and eliminated the need for the plastic case, reducing the thickness of back pocket to much closer to the thickness of the LightBlue Bean microcontroller. This design was not tested with users.

The design suggestions for an ABF to support core stabilization exercises were: Make sounds distinct through different timbres; Keep sound for correct alignment pleasant; Keep sounds simple; Sound for incorrect alignment needs to happen fast but not necessary in fast tempo. I also included a discussion on whether the StableBelt is intended to assist or substitute the physical therapist, describing the tasks that can be handled by the StableBelt, based on data gathered during the tests.

The tests conducted with the StableBelt left some open questions regarding the ABF. Further research is needed to elucidate these issues.

6.6
Future work

All participants were able to hear the distinction between sounds for correct and incorrect alignment in the third test. The percussion sound, and its tempo, used to inform incorrect alignment could be a source of discomfort, according to some participants. Some level of customization on the part of the user could improve on this sentiment. Further investigation is necessary with variations of the timbres used in this research or new timbres.. Inverting the direction of increasing tempo of the drum beats would be relevant to assess the best alternative or whether to leave it to be configured by the physical therapist or patient.

Exploring verbal encouragement triggered by simple conditions is an area that may be very fruitful. This could gradually evolve to increasing complexity of trigger that take into consideration results of previous verbal encouragements, measured via sensors, to enable adaptive intelligent triggers.

In the second cycle of the action research, I explored two LightBlue Beans communicating simultaneously with the computer. Future research in this area would enable the StableBelt to be used in standing exercises, such as squatting, and get audio feedback on whether patient is able to maintain “neutral spine”.

Testing the StableBelt, with patients suffering from NSLBP, with different degrees of severity, would be desirable, as our understanding of its effects on individuals without pain evolves and adequate testing procedures are developed. These tests would allow us to generalize the results to those who might benefit the most from the StableBelt.

Tele-rehabilitation could be explored by to taking the logs generated by the StableBelt prototype and store them on the cloud. This would add a new dimension to the StableBelt. Giving the ability to look at patient history and evolution. Looking at patterns and trends within and across individuals.

The current research was focused on audio feedback. Other modalities such as ambient visual feedback or vibrotactile could be added to investigate how these interact with core stabilization exercises. The support for ambient visual feedback is already partially in the prototype, since most of the MacBook screen changes color as the participant changes modes during the exercise, depending on the level of lighting in the room, this changes could be visible without looking directly at the computer. Both of these directions are aligned with the initial design decision to make the StableBelt not rely on visual feedback that would require the patient to need to dedicate his attention and gaze to a visual display. Having other modalities would enable us to compare how much users like the auditory mode of receiving feedback or how best to create a multi-modal interface.

These few topics for further research serve to provide a glimpse on the work that I just scratched the surface, but already show the promise of mixing simple musical feedback, with motion sensors and core stabilization exercises.

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Appendix A – Semi-structured interview (in Portuguese)

Questionário para StableBelt

Data: ______ / ________ / 2015

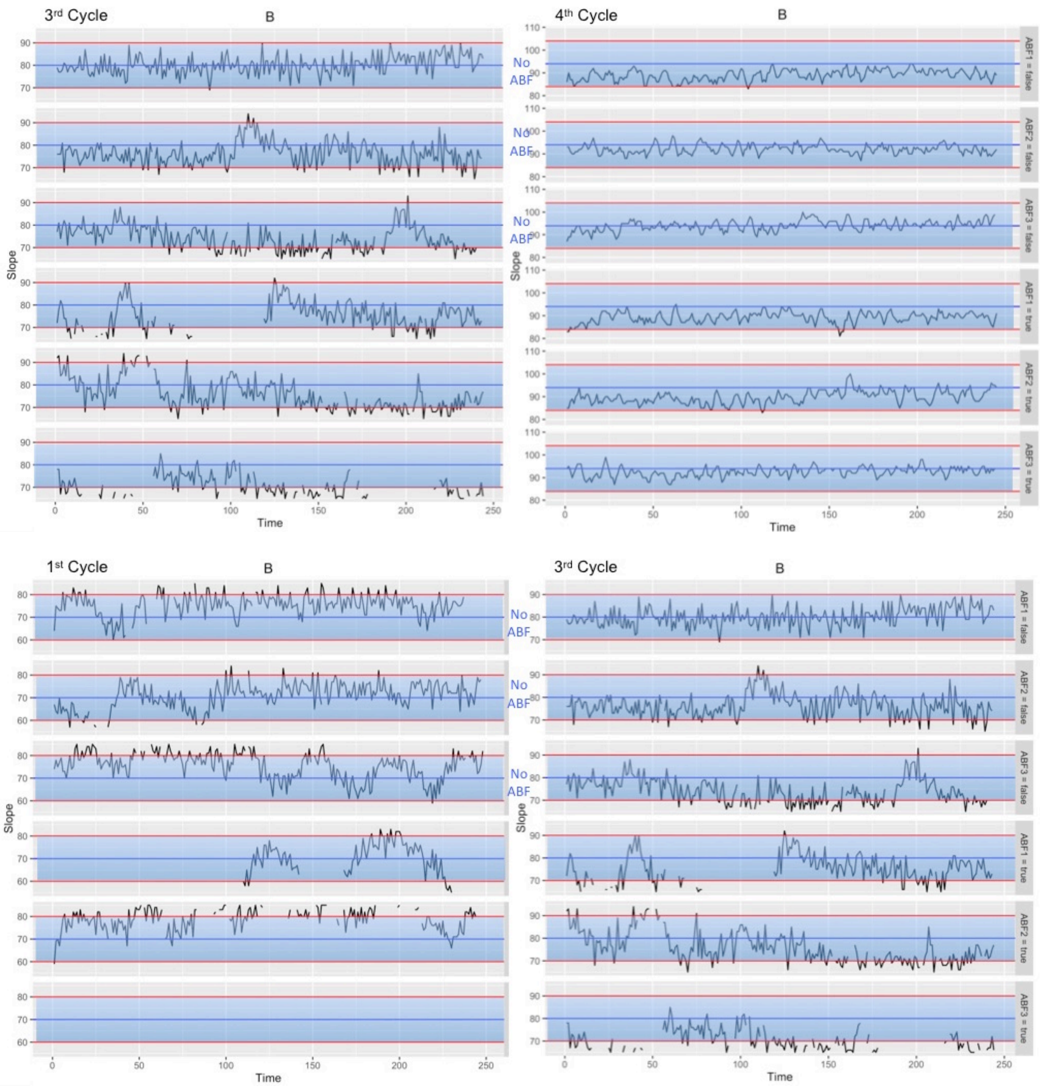
Nome: ____

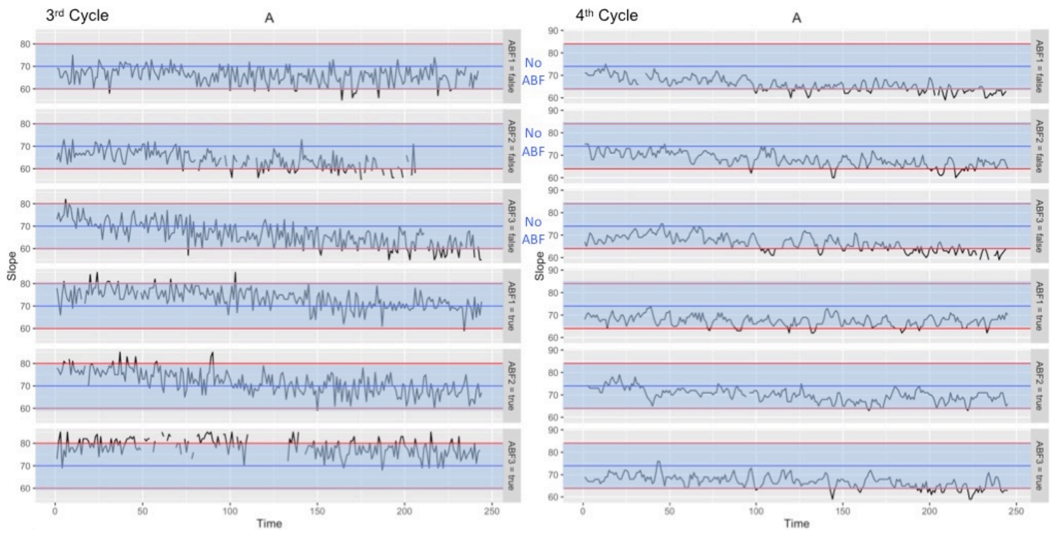
Idade: _____ Sexo: M / F

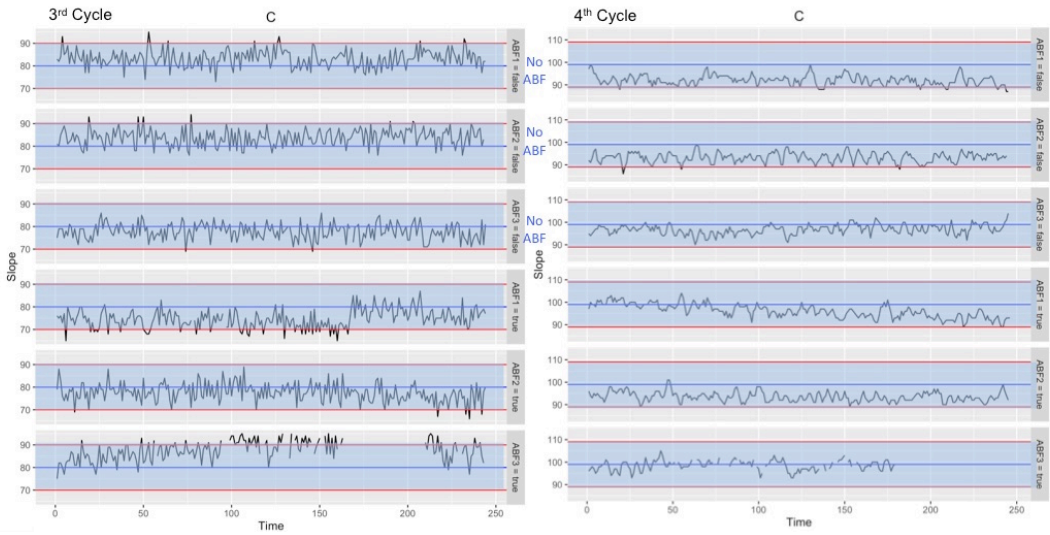
1. O que você gostou do StableBelt?
2. O que você não gostou StableBelt?
3. O feedback (retorno) ajudou?
4. O que você mudaria para melhorar o feedback (retorno)?
5. O que você mudaria na cinta?
6. Como foi a experiência de usar o StableBelt?
7. Os comandos estavam claros?
8. Sentiu necessidade de usar o mouse para avançar?
9. O que achou da duração do descanso?
10. O que achou da duração do exercícios? (Manter o quadril no alto por 22 segundos)

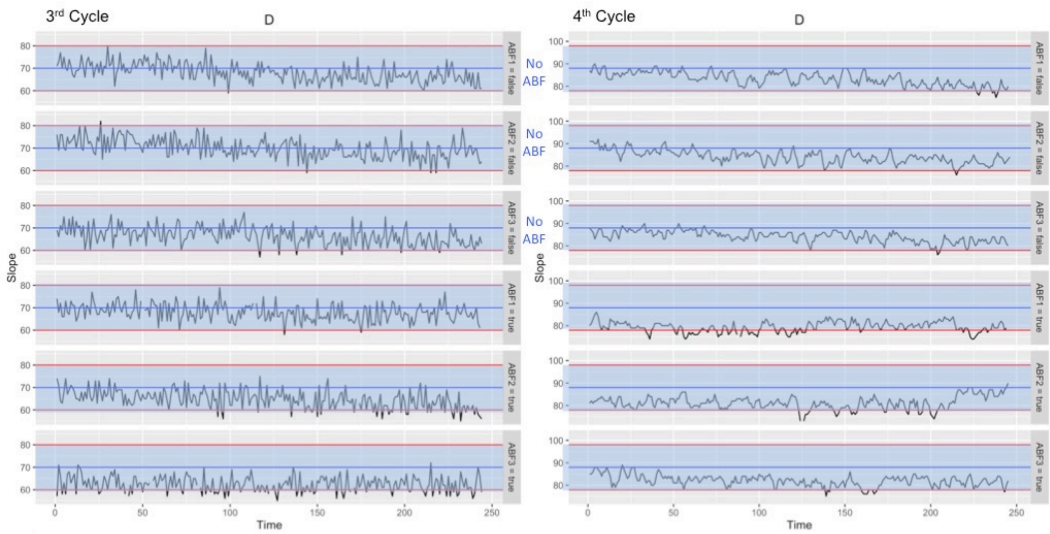
Appendix B – Graphs from User Tests

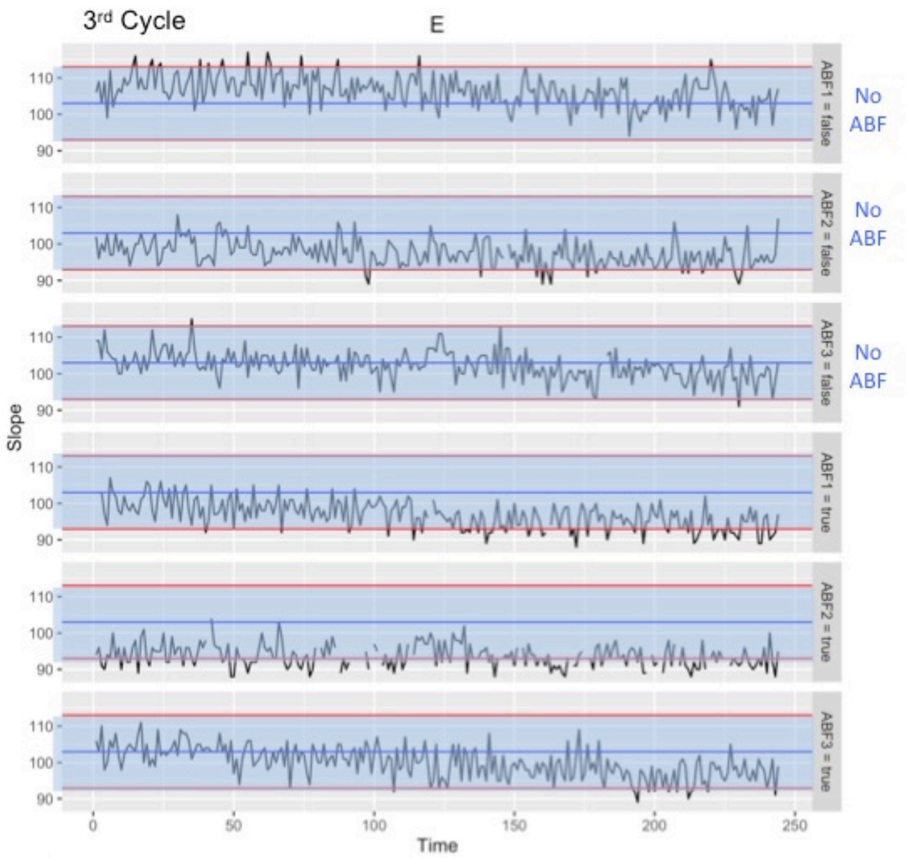
These graphs represent data from logs. Graphs are shown side by side, for participants were in multiple tests. Top 3 lines show data for repetitions without ABF and bottom 3 lines show data for repetition with ABF. Red lines represent the boundaries for correct alignment. The blue line represents the goal value. The black line represents readings from the y-axis of the accelerometer.

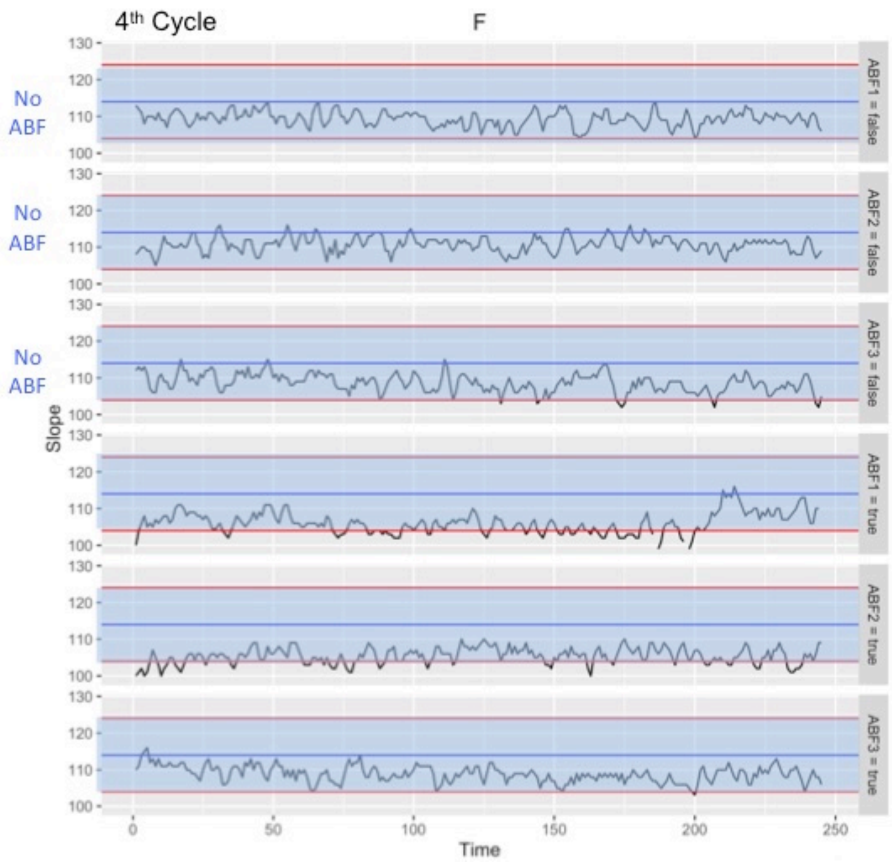


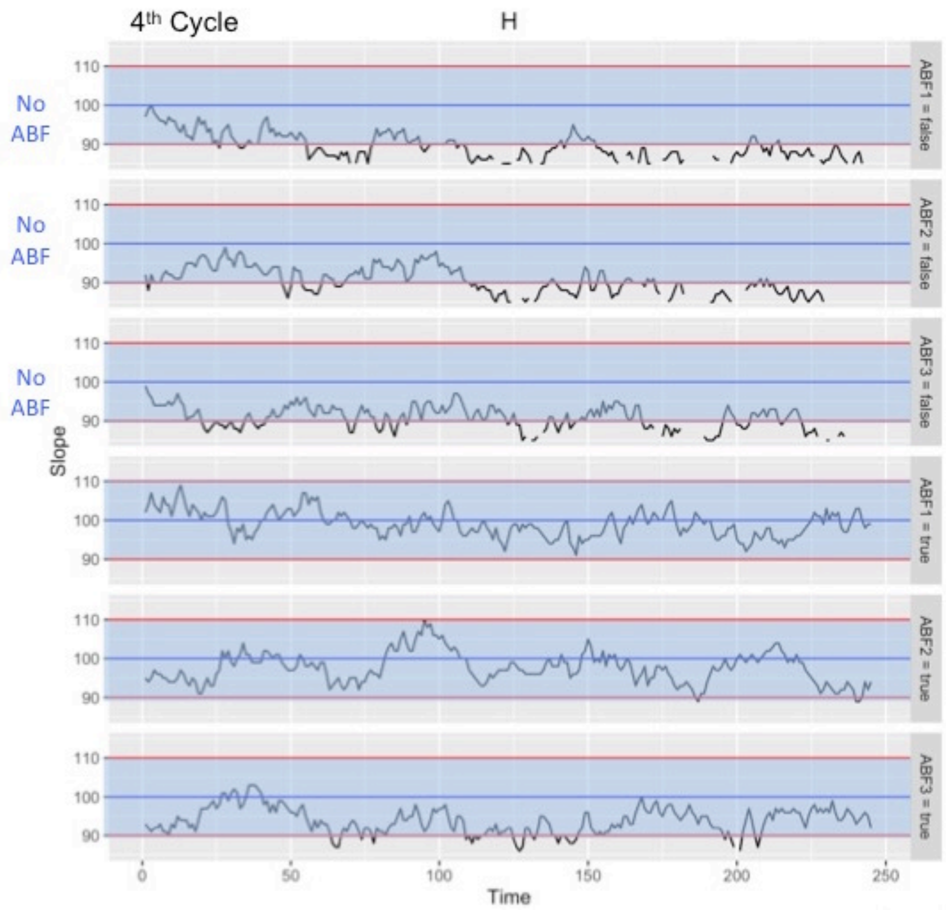

3rd Cycle
A
4th Cycle
A
No ABF
ABF1 = false
ABF2 = false
ABF3 = false
ABF1 = true
ABF2 = true
ABF3 = true
Slope
Time

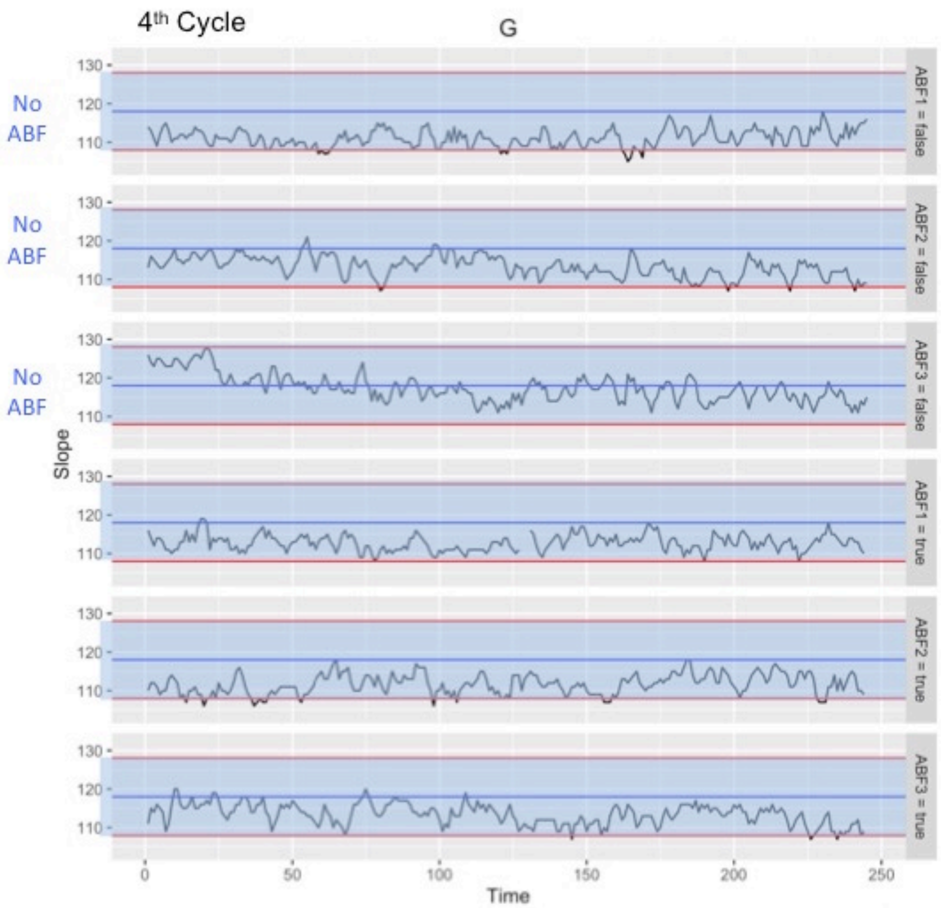

3rd Cycle
C
4th Cycle
C
No ABF
ABF1 = false
ABF2 = false
ABF3 = false
ABF1 = true
ABF2 = true
ABF3 = true
Slope
Time

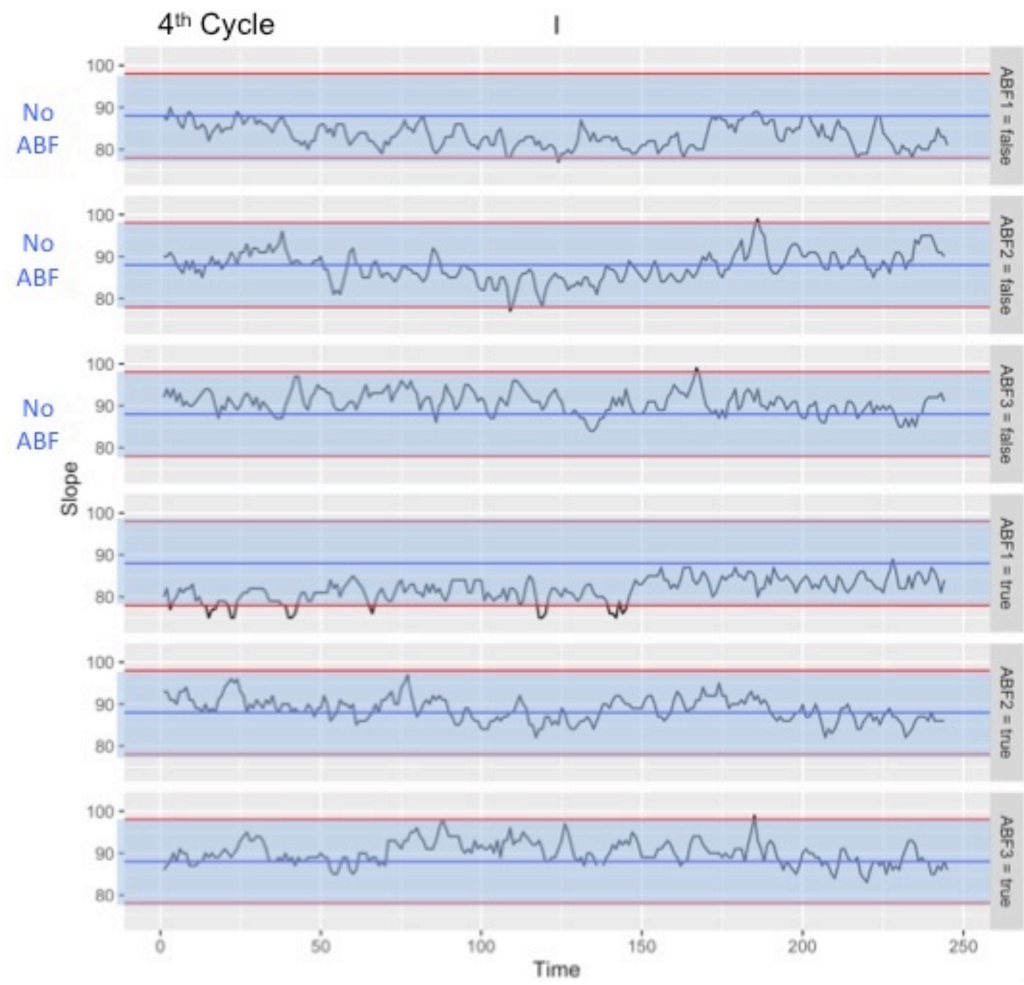

3rd Cycle
D
4th Cycle
D
No ABF
ABF1 = false
ABF2 = false
ABF3 = false
ABF1 = true
ABF2 = true
ABF3 = true
Slope
Time


3rd Cycle
E
No ABF
No ABF
No ABF
ABF1 = false
ABF2 = false
ABF3 = false
ABF1 = true
ABF2 = true
ABF3 = true
Slope
Time
0 50 100 150 200 250
90 100 110


4th Cycle
F
No ABF
No ABF
No ABF
ABF1 = false
ABF2 = false
ABF3 = false
ABF1 = true
ABF2 = true
ABF3 = true
Slope
Time
0 50 100 150 200 250
100 110 120 130


4th Cycle
H
No ABF
No ABF
No ABF
Slope
Time
ABF1 = false
ABF2 = false
ABF3 = false
ABF1 = true
ABF2 = true
ABF3 = true
110
100
90
0
50
100
150
200
250


4th Cycle
G
No ABF
No ABF
No ABF
Slope
Time
ABF1 = false
ABF2 = false
ABF3 = false
ABF1 = true
ABF2 = true
ABF3 = true
130
120
110
0
50
100
150
200
250


4th Cycle
No ABF
No ABF
No ABF
ABF1 = false
ABF2 = false
ABF3 = false
ABF1 = true
ABF2 = true
ABF3 = true
Slope
Time
100
90
80
0
50
100
150
200
250

Appendix C – Research Protocol (in Portuguese)

Projeto de Pesquisa

Biofeedback na Reabilitação

Proposta de Dissertação de Mestrado

Pesquisador: Fernando Cardoso Ismério – candidato ao título de Mestre em Ciências em Informática pelo Departamento de Informática da Pontifícia Universidade Católica do Rio de Janeiro *http://lattes.cnpq.br/3946426612156364*

Contato: *fismerio@inf.puc-rio.br*

Orientador: Profs. Hugo Fuks (*hugo@inf.puc-rio.br*)

Endereço: Rua Marquês de São Vicente, 225, Gávea - Rio de Janeiro

Sumário

1 Introdução

Este documento apresenta os objetivos e descrição de linhas gerais para projeto de pesquisa a ser realizado como tema de dissertação de mestrado em Informática no DI na área de concentração de Interação Humano-Computador (IHC), focando em *Wearables* para desenvolver avanços científicos e tecnológicos no domínio da Reabilitação.

2 Contextualização

A seguir apresentamos os conceitos do trabalho a ser feito.

2.1 Biofeedback

O biofeedback tem sido usado amplamente em reabilitação (Giggins, et al., 2013). As técnicas de biofeedback são divididas em duas categorias: Fisiológicas e Biomecânicas. As técnicas fisiológicas são mais antigas e mais associadas com o termo biofeedback. Dois exemplos usados nos exercícios de estabilização são: Eletromiografia (EMG) e ultrassom de imagem (RSTUS).

Nesta pesquisa, estamos interessados em técnicas biomecânicas, especificamente as que lidam com movimento. O biofeedback de movimento tem sido usado predominantemente no treino de equilíbrio e no treino de marcha.

2.2 Sensores de movimento

Para o biofeedback de movimento são usados: sensores de inércia e *camera-based systems* (Giggins, et al., 2013). Os sensores de inércia incluem: acelerômetro, giroscópio, e magnetômetro. Nesta pesquisa, estamos interessados em investigar o uso do acelerômetro na geração do biofeedback sonoro para exercícios de estabilização lombopélvica.

Muitos avanços têm ocorrido na área de sensores eletrônicos. Acelerômetros hoje são adquiridos a baixo custo e integrados com micro controladores, possibilitando novas estratégias para biofeedback biomecânicos. Acreditamos que os exercícios de estabilização lombopélvica se beneficiam do biofeedback sonoro gerado por acelerômetros. O acelerômetro estará posicionado em uma cinta e desta forma funciona como um *wearable.*

2.3 Exercícios de Estabilização Lombopélvica

Cerca de 50% da população sofre de dores lombares em algum momento da vida e muitas destas desenvolvem dores crônicas (Richardson, 2004). Grande número de estudos existe nesta área e muitos concluem que os exercícios de estabilização lombopélvica são um aliado importante no tratamento e prevenção destas dores. Estes exercícios seguem uma progressão de três fases: 1. Controle de estabilizadores locais, 2. Exercícios lentos com cadeia fechada, 3. Exercícios rápidos com cadeia aberta**.** A segunda fase inclui os exercícios de Ponte, que serão o foco da nossa pesquisa. Para executar o exercício de Ponte, o participante deita em decúbito dorsal, joelhos flexionados e pés apoiados. Ele eleva o quadril até alinhar coxas, tronco e ombros e mantem esta posição durante o tempo estipulado. Ao final deste período, o participante retorna a posição original.

2.4 Este Trabalho

Neste trabalho, buscamos investigar *Wearables* para desenvolver avanços científicos e tecnológicos no domínio da Reabilitação. As pesquisas relacionadas aos exercícios de estabilização fazem uso do biofeedback por EMG ou ultrassom. O biofeedback de ultrassom é sempre visual e o biofeedback por EMG é comunicado de várias formas (e.g., sonoro). A ausência de estudos usando acelerômetros ou sensores de inércia para exercícios de estabilização e os avanços da tecnologia nesta área, oferecem uma oportunidade para pesquisa. Acreditamos que esta pesquisa é relevante e justificada pelas possíveis implicações para o tratamento de dor lombar. Caso o resultado da pesquisa seja positivo, novas opções para auxiliar os exercícios de estabilização lombopélvica se tornam possíveis.

3 Participantes

Os participantes desta pesquisa são adultos sem problemas graves de saúde, capazes de executar os exercícios de estabilização lombopélvica, especificamente os exercícios de Ponte.

4 Objetivos

Após uma revisão preliminar da literatura, percebemos a possibilidade de investigar *Wearables* na Reabilitação, gerando biofeedback sonoro com sensores de movimento. Visamos os seguintes objetivos concretos:

- *Prototipar dispositivo de biofeedback sonoro;*
- *Realizar estudo preliminar de biofeedback sonoro para auxiliar na execução de exercícios de estabilização lombopélvica;*
- *Avaliar o sistema através dos dados coletados.*

5 Metodologia

Apresentamos a seguir a metodologia de pesquisa a ser adotada e suas justificativas principais.

5.1 Pesquisa quantitativa

A pesquisa que pretendemos desenvolver necessita de um experimento com controle da variável biofeedback. O uso do acelerômetro integrado a um micro controlador possibilita a coleta de dados de movimento com precisão e geração de biofeedback sonoro. Os movimentos do quadril durante o exercício são registrados em um *log*.

5.2 Experimento

Dentre os métodos quantitativos propostos para realizar investigações sobre o uso de sistemas computacionais, o experimento é um deles (Dennis & Valacich, 2001). No experimento, a precisão dos dados é o aspecto mais importante e, para isto, o controle das variáveis é essencial. Neste método, o realismo para os participantes e a generalização dos resultados com respeito as populações têm menor importância.

Cada participante executa o exercício de Ponte seis vezes com intervalo para descanso entre as repetições. Três repetições são feitas com biofeedback e as outras três sem biofeedback. A ordem é aleatória para eliminar efeitos de fadiga e de aprendizado motor.

5.3 Participantes

Testes com usuários são uma prática comum nas pesquisas de IHC (Barbosa, 2010). Para uma pesquisa sobre biofeedback em exercícios de estabilização lombopélvica não é necessário sujeitos com dor lombar, porque existem pesquisas anteriores que estabelecem a eficácia destes exercícios no tratamento da dor lombar (Richardson, 2004).

5.4 Coleta e análise dos dados

Serão utilizados logs com os dados gerados pelo acelerômetro. Durante o processo de prototipação e testes piloto, será escolhida a melhor métrica que represente o grau de estabilização durante o exercício assim como a relação entre os dados do acelerômetro e o biofeedback sonoro gerado.

6 Plano de Trabalho

Este projeto se propõe a ser desenvolvido dentro do prazo normal para conclusão do curso de Mestrado em Informática da PUC-Rio, que é de 18 meses até a defesa da proposta de dissertação e 6 meses adicionais para a pesquisa e conclusão da dissertação (Coordenação de Pós-Graduação - Departamento de Informática - PUC-Rio, 2013). Estou apresentando esta proposta de pesquisa no início de meu 18º mês do programa de mestrado, antecipando o Exame de Proposta de Dissertação (até o 18º mês) e o início da atividade de pesquisa (que se estende até o 24º mês). Assim sendo, as atividades foram programadas de modo a serem compatíveis com este contexto. A seguir apresentam-se cronograma e os custos previstos.

6.1 Cronograma

Em suas atividades principais, o projeto deverá transcorrer aproximadamente como abaixo:

Tarefa	Data
Questão	Julho 2015
Planejamento	Agosto 2015
Protótipo	Sep. 2015
Experimento	Out. 2015
Análise	Nov. 2015
Conclusão	Dec. 2015

6.2 Orçamento

O projeto conta com a participação de um pesquisador principal e seu professor orientador. Não há orçamento previsto especificamente para este projeto além dos contratos de trabalho dos professores envolvidos, bolsas de pesquisa e produtividade de que já dispõe e financiamento acadêmico normal do programa de pós-graduação do DI/PUC-Rio. Além destes, haverá os seguintes os custos específicos com equipamentos neste projeto:

Item	Valor	Fonte do recurso
Micro controladores, sensores e componentes para prototipação	~R$ 100,00	*Disponível para uso no Laboratório "SecondLab" do DI - Prof. Hugo Fuks*

7 Aspectos Éticos do Projeto

Desde a fase de concepção do projeto, o pesquisador principal mostra-se atento às questões éticas de seu trabalho, conforme direcionado pelo seu professor orientador.

Entendemos que este projeto merece uma reflexão ética sobre quatro dimensões:

- *Sobre os seus objetivos, e o valor dos mesmos;*
- *Sobre os seus artefatos, e as possíveis consequências dos seus usos;*
- *Sobre os seus métodos, e a validade científica dos possíveis resultados;*
- *Sobre os seus procedimentos, especificamente no que diz respeito à pesquisa envolvendo seres humanos.*

7.1 A Ética nos objetivos do projeto

Acreditamos que seja social e cientificamente relevante produzir avanços científicos e tecnológicos no domínio da reabilitação. Não enxergamos, até o momento, se e como tais objetivos seriam prejudiciais a alguma parcela da sociedade.

7.2 A Ética nos artefatos do projeto

Sem discutir as implicações relacionadas ao uso e adoção de tecnologia na sociedade atual em suas diversas facetas, assumimos que os artefatos produzidos por nossa pesquisa não introduzem questões adicionais às já enfrentadas em nosso dia-a-dia, com os artefatos de tecnologia já existentes e usados amplamente a nossa volta. Devemos, no entanto, estar sensíveis às discussões sobre os efeitos tanto das tecnologias atuais como das modificações ou modos de utilização que viermos a promover com a nossa pesquisa. Para isso, contamos com fatores que, acreditamos, tornam esta reflexão possível e nos dão segurança para a condução deste trabalho de forma ética:

- *A sólida experiência em pesquisa e formação do professor orientador em Ciência da Computação e especificamente na área de Interação Humano-Computador, o que imprime ao projeto um olhar atento e cuidadoso para os usuários;*
- *A interação constante com outros pesquisadores experientes neste assunto através de reuniões com o orientador;*
- *A submissão do projeto ao sistema CEP/CONEP, com o objetivo de que este possa dar o seu parecer de um ponto de vista ainda mais externo e especializado nesta questão.*

7.3 A Ética nos métodos e validade científica dos resultados

Com uma pesquisa quantitativa, pretendemos obter, resultados estatisticamente significativos com este trabalho. Em uma pergunta, nossa questão principal é sintetizada da seguinte forma: *o uso de biofeedback sonoro gerado por sensores de movimento melhora a execução de exercícios de estabilização lombopélvica?* Nosso estudo investigará temas relevantes para IHC, de modo geral, e também Interfaces Tangíveis e Reabilitação. Esperamos responder nossa questão através da análise dos dados coletados durante o experimento. Embora nossa amostra seja relativamente pequena, acreditamos que teremos resultados preliminares sobre biofeedback sonoro neste aspecto da reabilitação e que estudos futuros irão aprofundar nossos achados. Esperamos que tais questões interessem à comunidade científica, através de uma continuação ou de estudos complementares.

A coleta e análise de dados será semelhante aos estudos sobre equilíbrio e controle postural. Seguiremos as recomendações padrão de uma pesquisa quantitativa que busca a qualidade com a atenção aos detalhes do planejamento e execução do experimento.

7.4 A Ética nos procedimentos de uma pesquisa envolvendo seres humanos

Sobre este aspecto, iremos dar cumprimento das normas regulamentadoras aprovadas na Resolução nº 196/96, do Conselho Nacional de Saúde (COMISSÃO NACIONAL DE ÉTICA EM PESQUISA - CONSELHO NACIONAL DE SAÚDE - MINISTÉRIO DA SAÚDE, 2012) e na Resolução nº 466/12, do Conselho Nacional de Saúde (CONSELHO NACIONAL DE SAÚDE - MINISTÉRIO DA SAÚDE, 2012).

Os participantes da pesquisa compreendem uma população que envolverá no mínimo 8 indivíduos, que serão adultos saudáveis, capazes de executar o Exercício de Ponte (ver seção 5.3). Todos são maiores de idade, plenamente autônomos, de classes sociais média e baixa, com profissões e papéis variados.

Os riscos destes estudos são pequenos e serão minimizados e administrados da seguinte forma:

- *A explicação detalhada dos objetivos e das etapas da pesquisa para os participantes;*
- *A apresentação do equipamento, instruções de uso e seus riscos envolvidos de forma clara e detalhada para os participantes de modo a permitir suas decisões informadas;*
- *A garantia do anonimato das informações colhidas por meio de quaisquer métodos e técnicas (entrevistas, questionários, observações de campo, coleta de dados automática do sistema, etc.) e, em particular, a garantia da preservação da imagem nos casos em que se recorra a fotografias ou vídeos de um ou mais participantes;*
- *A descrição do instrumento de coleta usados na pesquisa (sensor de movimento), acompanhada das razões para sua utilização;*
- *O caráter voluntário de participação na pesquisa e a possibilidade de interromper temporária ou definitivamente esta participação a qualquer momento;*
- *A leitura e a assinatura do "Termo de Consentimento" (ver* Anexo I – Termo de Consentimento Livre e Esclarecido*), emitido em duas vias, após a explicação oral e informal dos tópicos acima;*

- *Execução da pesquisa propriamente dita, conduzida por um único pesquisador principal da equipe, de forma supervisionada pelo seu professor orientador;*
- *O oferecimento de acesso às publicações científicas futuras resultantes da pesquisa da qual o entrevistado participou.*

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http://conselho.saude.gov.br/resolucoes/2012/Reso466.pdf

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Anexo I – Termo de Consentimento Livre e Esclarecido

O termo aparece na próxima página para manter a formatação.

Título da pesquisa: *Biofeedback na Reabilitação*

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Participante: ____________________________________

Caro(a) participante,

Desenvolvemos aqui no Departamento de Informática da PUC-Rio diversas pesquisas na área da Interação Humano-Computador (IHC) que estuda teorias, métodos e tecnologias para projeto, avaliação e implementação de sistemas interativos, bem como dos fenômenos ao redor deles. Com grande honra gostaríamos de convidar você para participar de nossa pesquisa, que busca investigar *Wearables* e *Biofeedback* para desenvolver avanços científicos e tecnológicos no domínio da Reabilitação.

Propósito: O objetivo desta pesquisa é entender se o biofeedback gerado por sensores de movimento pode auxiliar nos exercícios de estabilização lombopélvica. Participantes serão solicitados a utilizar um dispositivo de interação e software especial capaz de gerar biofeedback. A realização das tarefas será observada e dados serão coletados pelos sensores de movimento para avaliar se a tecnologia desenvolvida pode oferecer benefícios neste contexto.

Procedimentos: A participação neste estudo irá envolver três tipos de atividades. Primeiramente, você receberá um breve treinamento sobre como completar os exercícios.

Depois disso, você vai fazer os exercícios utilizando o sistema desenvolvido. Para isto, você vai vestir uma cinta confortável que inclui os sensores utilizados.

No final, poderemos questionar as suas impressões, opiniões, sensações e percepções sobre o uso da tecnologia.

Os procedimentos devem durar aproximadamente 30 minutos.

Coleta de dados: Os dados principais serão coletados através dos sensores de movimento. Faremos anotações, fotografias, gravações de áudio e vídeos quando houver necessidade, se você assim permitir, como forma de coletar dados adicionais para analisarmos posteriormente.

Riscos: As tecnologias a serem utilizadas são não-invasivas e confortáveis (uso de uma cinta elástica com pequena caixa plástica onde reside o sensor). Este uso estará limitado a duração dos exercícios. Você pode sentir cansaço ou desconforto durante a participação neste estudo. Serão concedidas todas as oportunidades necessárias para você interromper ou descansar. Você tem pleno direito de solicitar esclarecimentos adicionais, de interromper ou terminar as sessões quando e como quiser. Não há qualquer impedimento para isto nem qualquer necessidade de apresentar uma justificativa ou explicação.

Confidencialidade: As informações coletadas neste estudo serão tratadas dentro das normas éticas de conduta em pesquisa: 1) serão mantidas em arquivos e servidores seguros dentro do Departamento de Informática da PUC-Rio e serão acessíveis apenas pela equipe de pesquisadores envolvidas no projeto e somente com a finalidade de pesquisa que você consentir; 2) os resultados da pesquisa serão apresentados respeitando-se rigorosamente a sua privacidade e o anonimato de todos participantes, sem a divulgação de nomes, imagens e outros dados que permitam a sua identificação; 3) você poderá solicitar os resultados publicados desta pesquisa se e quando desejar.

Você pode solicitar esclarecimentos adicionais ou optar por não colaborar mais com este estudo a qualquer momento, temporária ou definitivamente, quando e como quiser. Não há qualquer impedimento para isto nem qualquer necessidade de apresentar uma justificativa ou explicação.

Para prosseguir, porém, pedimos que manifeste o seu consentimento por escrito marcando as opções abaixo e assinando este termo, do qual você receberá uma cópia para os seus arquivos:

Li e entendi as informações neste termo: ______

As informações neste termo foram explicadas e esclarecidas para mim: ______

Título da pesquisa: *Biofeedback na Reabilitação*

Consinto em participar das atividades descritas acima: ______

Autorizo o uso de fotografias, áudio, vídeos e dados de uso dos sistemas coletados sobre mim: ______

Rio de Janeiro,

_______________________________________ Data: ________________

Participante

_______________________________________ Data: ________________

Pesquisador

_______________________________________ Data: ________________

Testemunha