DISS. ETH NO. 27942

APPLICATION OF MOBILE SENSORS IN LOW BACK PAIN MANAGEMENT

A thesis submitted to attain the degree of
DOCTOR OF SCIENCES OF ETH ZURICH
(Dr. sc. ETH Zurich)

presented by
ANITA MEINKE
M.Sc., Universität Koblenz-Landau

born on *14.12.1990*
citizen of Germany

accepted on the recommendation of

Prof. Dr. Walter Karlen, ETH Zurich, examiner
Dr. Jaap Swanenburg, University of Zurich, co-examiner

2021

ABSTRACT

Treatments for low back pain (LBP) are often not very successful. It is assumed that aberrant movement behavior and unfavorable stress on the spine can provoke or consolidate LBP. Sensors which are able to precisely quantify these phenomena could provide great advantages for rehabilitation and research, therefore further exploration of this field is required. Exercises for people with LBP may be effectively supported by feedback on torso movements from sensors. In a pilot randomized controlled trial (RCT) we assessed the benefits and effect of such an intervention on movement behaviors and other variables. Although no statistically significant effect was observed, this result must be seen within the context of low adherence to the training schedule. Not only practice, but also other variables such as fears can influence movement in people with LBP. To show the influence of fear of movement on balance during quiet standing, we conducted secondary analyses on the data from the RCT. We further analysed, whether fear of movement on different body planes has a distinct impact on balance on different body planes. The results showed that fear of movement on the frontal plane could be especially relevant to balance.

Sensors may not only assist in the treatment of LBP, but also the prevention. As long-term exposure to repeated and high loads on the spine presumably promote the development of LBP, people at an increased risk may benefit from extensive monitoring of these risk factors. We propose that loads from ski training in young athletes could be effectively monitored and might be better manageable by relying on data from sensors in standard mobile phones. In support of this approach we present a case-study of an adolescent ski athlete. The results discussed in this thesis contribute to the current understanding of the use of sensor technology for LBP. Building on these results, future research directions are discussed.

ZUSAMMENFASSUNG

Therapien für Schmerzen im unteren Rückenbereich (SuR) sind oft nicht sehr erfolgreich. Es wird angenommen, dass abeweichendes Bewegungsverhalten und ungünstige Beanspruchung der Wirbelsäule SuR hervorrufen oder festigen können. Sensoren, die in der lage sind solche Phänomene präzise zu quantifizieren, könnten grosse Vorteile für die Rehabilitation und Forschung bieten, daher ist eine weitere Exploration dieses Bereichs erforderlich. Übungen für Personen mit SuR könnten effektiv durch Feedback zu Bewegungen des Torso unterstützt werden. In einer randomisiert kontrollierten Pilotstudie haben wir den Nutzen und Effekt einer solchen Intervention auf das Bewegungsverhalten und andere Variablen bewertet. Obwohl kein statistisch bedeutsamer Effekt beobachtet wurde, muss dieses Ergebnis im Kontext des geringen Einhaltens des Trainingsprogramms gesehen werden. Nicht nur Übung sondern auch andere Variablen so wie Ängste, können die Bewegungen von Personen mit SuR beeinflussen. Um zu zeigen wie die Angst vor Bewegung die Balance während des Stillstehens beeinflusst, haben wir Sekundäranalysen der Daten der randomisiert kontrollierten Studie durchgeführt. Weiterhin haben wir analysiert, ob Angst vor Bewegung in unterschiedlichen Körperebenen einen Einfluss auf die Balance in den unterschiedlichen Körperebenen hat. Die Ergebnisse zeigen, dass Angst vor Bewegung auf der Frontalebene besonders bedeutsam für die Balance sein könnte.

Sensoren könnten nicht nur die Behandlung von SuR unterstützen, sondern auch die Prävention. Da die dauerhafte Exposition zu wiederholten und hohen Belastungen der Wirbelsäule die Entwicklung von SuR vermutlich fördert, könnten Personen mit einem erhöhten Risko von ausgdehnterer Überwaschung dieser Risikofaktoren profitieren. Wir schlagen vor, dass Belastungen durch das Ski training junger Athleten effektiv beobachtet werden könnte und besser zu kontrollieren wäre, indem auf die Daten von Sensoren in gewöhnlichen Mobiltelefonen zurückgegriffen wird. Um diesen Ansatz zu unterstützen stellen wir eine Fallstudie über einen jungen Ski-athlet vor. Die Ergebnisse welche in dieser Dissertation besprochen werden tragen zu dem aktuellen Verständnis der Nutzung von Sensor-technologie für SuR

bei. Auf den Ergebnissen aufbauend wereden zukünftige Forschungsrichtungen disktuiert.

ACKNOWLEDGEMENTS

I am more than grateful to my Professor Walter Karlen, for support and supervision and for the opportunity to do this work. I also would like to thank Jaap Swanenburg for supervision and guidance, especially in the study conduction. I am genuinely grateful to you both, and for all the things I was able to learn during this time. Jörg Spörri, Lars Lünenburger, Michael Meier, Prof. Oliver Distler, Rick Peters, Ronald Stam, Ruud Knols have supported me with these projects, I really appreciated to work together with you and would like to thank you for your contributions in the projects. I would like to thank my colleagues Caroline Lustenberger, Gaetano Scebba, Giulia Da Poian, Jelena Dragas, Jia Zhang, Kanika Dheman, Ku-young Chung, Laura Ferster, Laura Tüshaus, Monica Moreo, Michela Rimensberger and Patrick Schwab. I was very lucky to have you as my coworkers. I would also like to thank all students and colleagues who worked together with me on the projects Adrian Stutz, Cinzia Maschio, Katharina Zahoranszky, Kim Graf, Luzius Brogli, Ramon Glättli, Tina Wunderlin and Yanick Riederer. In addition I would like to thank the participants who have taken the effort to participate in this research. I would in particular like to thank my family Sabine, Hermann, Carina and Martin Meinke and my friends for the support during this PhD and before.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AP: Anterior-posterior
COP: Center of pressure
IMU: Intertial measurement unit
ML: Medio-lateral
NRS: Numeric rating scale
PHODA-SEV: Photograph Series of Daily Activities-Short Electronic Version
QOL: Quality of life
RMDQ: Roland Morris disability questionnaire
ROM: Range of motion
TSK-11: Tampa scale for Kinesiophobia-11 item version
UHZ: University Hospital Zurich

1 INTRODUCTION

Low back pain (LBP) is among the 5 conditions responsible for most disability across all 21 areas covered by the global burden of disease study (Wu et al., 2020). Expectations of patients towards the clinicians' expertise and the offered solutions are high, given the commonality of LBP. However, pain is determined by a complicated mix of aspects that can differ between patients (Fillingim, 2017). Thus, the rather general, unspecific guidance patients receive (Maher et al., 2017) stands in a sharp contrast with the experience of possibly strong, frightening pain. Current therapy guidelines recommend to pursue physical activities as usual for people with acute pain and exercise interventions for chronic pain, but do not agree on which kind of exercise to promote (Oliveira et al., 2018). Exercising can reduce chronic LBP to some degree (Hayden et al., 2005; Middelkoop et al., 2010; Saragiotto et al., 2016). However, studies aimed at describing paths of temporal development in the population suggest that LBP often persists (Lemeunier et al., 2012).

Technological advances and digitalization have resulted in the development of a range of tools that create opportunities for monitoring LBP and delivering interventions. Mobile health (mHealth) tools used in combination with standard of care reduce pain intensity and improve disability in LBP patients (Chen et al., 2021). Sensing capabilities of such tools could be used to measure contextual situations or interventional opportunities, as for example seen in the study of Rabbi et al. (2018). Furthermore, to advance the treatment and knowledge about LBP, the capabilities of these technologies can be explored more extensively. For example large data sets collected in the field could provide information that otherwise would not be easily accessible. This should however not go without placing the technological advances in relation to the existing knowledge about influential factors on LBP.

In this thesis I present three unique contributions that bring together sensor-based technologies to investigate LBP. I shed light on three different research questions:

1. **Do digital, sensor-based interventions bring a benefit for people with LBP?** We investigated the effect of a technology driven exercising intervention on motor behavior and psycho-social factors in a home environment.
2. **How do psycho-social variables and the motor system interact in people with LBP?** We explored the influence of fear of movement on postural balance in people with LBP.
3. **Can we apply real world big data sensing to track factors that may enhance the risk of LBP?** We present a case study on unobtrusive technological solutions for monitoring the training activity on the ski hill to estimate effective training time in adolescent skiing athletes.

1.1 LOW BACK PAIN

Different, mostly elusive underlying mechanisms and conditions can provoke pain in the lumbar region (Maher et al., 2017). LBP without a located source is then referred to as "nonspecific" (Maher et al., 2017). The cutoff for describing LBP as chronic is uniformly pinpointed by guidelines to 12 weeks, but the intervals given for the acute phase differ (Oliveira et al., 2018). Pain has been described as *"... sculpted by a mosaic of factors unique to the person, which renders the pain experience completely individualized."* (Fillingim, 2017, p. S11). Thus, therapists and researchers face a high degree of heterogeneity when working with pain (Fillingim, 2017). In particular, diversity in alterations of motor behavior occur together with LBP (Dieën et al., 2019). Exercise interventions that target motor control are actively investigated (Weng et al., 2020), but the effectiveness of interventions may be confined by the limited insights into motor control in the first place (Van Dieën et al., 2017).

1.1.1 *Risk factors*

Among others, *"...risk factors might be the hot topic[]"* (Weng et al., 2020, p.11) in upcoming LBP research. A recent review of reviews confirmed variables from the broader domains mental stress, physiological loads, and other health complaints as risk factors (Parreira et al., 2018), although even at the level of reviews the results diverge for physiological loads (Swain et al., 2020). Lack of physical activity was found to be associated with an elevated likelihood of LBP in comparison with an intermediate degree of physical activity (Alzahrani et al., 2019; Heneweer et al., 2009). On the contrary, for people in jobs with a higher demand of physical activity the relationship might be reversed and time spent seated could rather help to prevent LBP (Øverås et al., 2020). These results could be in line with the "U-shaped" connection between activity and LBP that had been confirmed earlier (Heneweer et al., 2009). However, the authors from all mentioned physical activity reviews agree that different kinds of activities might have to be considered separately (Alzahrani et al., 2019; Heneweer et al., 2009; Øverås et al., 2020). In addition, higher fears in people who had LBP for a few weeks to three months seem to indicate an increased likelihood for unfavorable outcomes (Wertli et al., 2014). Some risk factors may be actively changed by intervention (Parreira et al., 2018).

1.1.2 *Motor behavior in people with LBP*

Despite the pessimistic view outlined above, several advances have been made in the past years. Earlier assumptions, for example bending in the lumbar region during lifting would promote LBP through unfavorable loading, are now called into question, as a meta-analysis opposes this view (Saraceni et al., 2020). Observable motor behavior can be a consequence, but also plays a role in the genesis of pain (Dieën et al., 2019). Irrespective of the processes that lead to these differences, it has been proposed to group people with LBP into those who tend towards restriction, and those who tend to relax the body (Dieën et al., 2019). Restricted (Van Dieën et al., 2017; Dieën et al., 2019) or relaxed (Dieën et al., 2019) body movement in reaction to pain may ultimately even worsen LBP. Modifications in motor control elicited by an episode of pain are thought to partially be learned behaviors (Van Dieën et al., 2017).

1.1.3 *Fear and motor control in people with LBP*

Besides the effect that psychological aspects can have on the restoration of health, such as the impact of fear on the ability to take up their job (Wertli et al., 2014), fears can also relate to movement. For example a meta-analysis showed that fears are linked to a more restricted movement of the spine, albeit only to a minor degree (Christe et al., 2021). Analogous patterns were found for depressive symptoms and catastrophic thoughts (Christe et al., 2021). Van Dieën et al. (2019) wrote that such movement pattern modifications when driven by fear without physical need could be detrimental to LBP. First evidence points toward an interference of fear with the degree to which people with chronic LBP are able to control their lumbar region precisely (Alsubaie et al., 2021).

1.1.4 *Exercise interventions*

Next to pharmacological treatment, exercise interventions are among the preferred treatment options for chronic LBP (Oliveira et al., 2018). People with chronic (Hayden et al., 2005; Middelkoop et al., 2010; Saragiotto et al., 2016), but not acute LBP (Hayden et al., 2005) respond to exercise treatments. Nevertheless, the benefits are oftentimes meager (Hayden et al., 2005; Middelkoop et al., 2010). Although the studies do not suggest that treatments of motor control exceed the performance of alternatives (Saragiotto et al., 2016), they seem to have received ample coverage in scientific publications on LBP (Weng et al., 2020). Approaches that focus on learning of movements such as motor control exercises (Saragiotto et al., 2016) may especially benefit from the integration of technology, as feedback from sensors may enhance this learning process. It was already noted in the review of Saragiotto et al. (2016) that technological solutions had been integrated in interventions included in their review, such as in the study of Macedo et al. (2012), where ultrasound imaging technology was used. Thus, the integration of such intervention approaches with technological solutions seems natural.

1.2 TECHNOLOGY AND DIGITALIZATION IN LBP

Digital technologies play an important role in LBP management and research. Interventions for LBP that applied some form of technology, whether for exercising (Matheve et al., 2017) or other mobile or remote interventions (Chen et al., 2021; Dario et al., 2017), produced better results when they were provided along with another intervention, and the effect tested against the other intervention by itself. A recent review by Chen et al. (2021) identified 9 studies that had digital interventions that are as simple as phone calls to support self-management, but can also include more complex, sensor supported exercises.

Another line of work relates to the use of digital technologies in LBP research. To support the research efforts in understanding the processes which drive LBP, technological advances offer new perspectives, such as that sensing technology can be used to monitor and investigate digital biomarkers in the field or the laboratory that are already known or suspected to be linked to LBP, as for example by Dixon et al. (2019) who assessed how pain behaves in relation to environmental circumstances by using mobile phones. For the sake of simplicity, we will divide the literature into applications that focus on prevention and applications for intervention.

1.2.1 *Sensor based prevention*

To not let people acquire LBP in the first place, it may be useful to track factors that have been confirmed to affect the likelihood of LBP negatively (Parreira et al., 2018). This may be especially the case for groups of people who are known to be at risk. For example, lifting heavy loads with a flexed back in a work context is typically seen as a risk factor. With the developing trend to track different kinds of health data, sensor based tools specifically targeting factors related to LBP can be developed. For example tools that measure spine posture in people who have to maneuver great weights (Pistolesi and Lazzerini, 2020). Also for the assessment of risk mobile health systems offer entirely new approaches. A study which clarified that chronic pain in general indeed depends to some degree on weather parameters, collected data which was provided by the participants themselves exclusively via mobile phones in a very large group (Dixon et al., 2019). This encompassed tracking of GPS data to extract the corresponding records from meteorological platforms later on (Dixon et al., 2019). The authors suggested that on the basis of such knowledge, it is imaginable that risk of pain may be predicted and made accessible to benefit people with pain directly (Dixon et al., 2019). This example shows how data from sensors included in mobile phones, although not the GPS data itself, may be highly relevant for research and in addition to users.

1.2.2 *Sensor based interventions*

As applications of sensors outside of a research context mostly have the ultimate goal to provide an intervention or to promote behavior change, the distinction between tracking and intervention is not always clear-cut. Even if the intervention may not be immediately delivered by the tracking device, as for example the spinal load tracking of Pistolesi et al. (2020), the collected data was used to determine which employees should receive instructions about lifting technique again. In other cases the users obtained feedback from the sensor-based tool directly, as for example in the studies of Ribeiro et al. (2014; 2020). While alerting the users when flexing the torso often and continued appeared to influence the movement behavior in a pilot study (Ribeiro et al., 2014), a later study carried out to confirm this effect discarded the findings (Ribeiro et al., 2020).

Exergames and virtual reality have attracted much interest and also games that were not primarily designed to improve LBP have been subsequently adopted. In 2013 an exergame for improving motor control in people with chronic pain was reported, however it was still based on external motion capture (Jansen-Kosterink et al., 2013). The WII (Kim et al., 2014; Zadro et al., 2019) and lately the Ring Fit adventure (Sato et al., 2021), both designed by Nintendo (Nintendo of America Inc., Redmond, WA, USA) have been successfully used to decrease pain in people with LBP. Other studies have used exergaming systems that are more geared towards rehabilitation in the first place (Alemanno et al., 2019; Hügli et al., 2015; Kent et al., 2015; Matheve et al., 2018b; Thomas et al., 2016). Some studies found intervention effects on several variables (Alemanno et al., 2019; Kent et al., 2015; Matheve et al., 2018b), but two studies had a one-group design (Alemanno et al., 2019; Matheve et al., 2018b) and one of them had used other training modalities along with the exergame (Matheve et al., 2018b). In two trials no training effect was found in comparison to a control group (Hügli et al., 2015; Thomas et al., 2016). However in one of these studies the duration of exercising was only 45 minutes altogether (2016), which might be much too little to show an effect on the chosen outcomes.

The intervention we will discuss in chapter two in more detail is the Valedo home (Hocoma AG, Volketswil Switzerland), which is another version of the systems used in two of the above mentioned studies (Hügli et al., 2015; Matheve et al., 2018b).

These studies have used the device mainly in addition to other therapies (Hügli et al., 2015; Matheve et al., 2018b), but more isolated estimates of the interventions effects would provide valuable information.

Next to wearable sensors, apps can be developed that make use of the sensors which are embedded in regular smartphones. An app for LBP with primarily sensor-based functionality is the MyBehaviorCBP app (Rabbi et al., 2018). This app fosters physical activity by drawing from past behaviours detected in a certain situation and proposes simple and manageable modifications (Rabbi et al., 2018). So far, participants in a study testing the concept were more active with the app proposing tailored, rather than random contents (Rabbi et al., 2018). To conclude, sensor-based interventions can have a positive impact, but these effects are not consistent. Clearly, more research is needed to identify which interventions should be promoted and how they could be further improved.

1.2.3 *Validation of technology*

The effects of technology based interventions should be analyzed and understood, before the use of these devices should be recommended. Mostly by making use of inertial measurement unit sensors (IMU), many different technical solutions for tracking the spine have been presented, and have focused on different conditions and health care applications (Simpson et al., 2019). However, these applications rarely have been sufficiently tested (Simpson et al., 2019). Devices which analyze spinal posture and alert people when movements defined as harmful are made (Ribeiro et al., 2014; Ribeiro et al., 2020) or capture the posture of the back during lifting (Pistolesi and Lazzerini, 2020) could be considered as examples.

> *"Monitoring how the loads are lifted is key to quickly detecting which workers are showing dangerous behaviors, so that they can be (re)trained to perform the task safely, thereby reducing the risk of injury."* (Pistolesi and Lazzerini, 2020, p.7199)

The statement highlights the assumptions about the harmfulness of spinal postures that are being made. This is in contrast with the conclusions from up-to-date evidence, according to which the majority of studies could not identify an association of lifting with a bent back and LBP, although the weights studied were rather low (Saraceni et al., 2020). Saraceni et al. (2020) stressed that the usual recommendation against lifting with a bent back are not underpinned by their findings. Moreover, the associations of LBP with postures and behaviors thought to place excessive strain on the spine remains unclear (Swain et al., 2020). However, it needs to be kept in mind that lifting method and occurring strain are separate concepts (Saraceni et al., 2020).

Pain related fears have been linked to less favorable betterment (Wertli et al., 2014) and devices which explicitly encourage avoidance of certain behaviors might also promote the development of fears. Nevertheless, these arguments do not disqualify the possible benefits such applications could have, but emphasize the need for thorough assessment of benefits and potentially unintended effects, even if the concept of an intervention seems reasonable. Preliminary results for one of the systems mentioned above (Ribeiro et al., 2014) indicated that using the device may reduce movements flagged as extreme. However, an additional, bigger study opposed this result (Ribeiro et al., 2020).

1.3 RESEARCH GAPS

Although research activity to study LBP was rising during the past two decades (Weng et al., 2020), many questions remain unanswered. In this thesis we will address three distinct research questions exploring options for the use of technology in tracking, treatment, and deepen our understanding of the multiple factors contributing to LBP.

1.3.1 *Sensor based technology for intervention*

> *1) Does exercising with feedback from sensors improve the motor system in people with LBP?*

As outlined above, testing of novel technological solutions with respect to their direct benefits for improving LBP, but also their effects on other related factors is required. Data on spinal and lumbar movement is collected for research purposes often, but is investigated less frequently for intervention. For example (Hügli et al., 2015; Kent et al., 2015; Magnusson et al., 2008; Matheve et al., 2018b) all have used interventions which made use of movement data of the back. In an experimental context indications have been found that sensors may be especially suitable to give feedback and foster the development good motor control (Matheve et al., 2018a). Some studies used assessments that required participants to reproduce a target signal by moving the torso or hip while receiving online displays of their movement (Alsubaie et al., 2021; Cavaleri et al., 2020; Willigenburg et al., 2013). One of these studies found that people with LBP completed the task more imprecisely (Willigenburg et al., 2013), which may imply that people with LBP could benefit from training of similar tasks. A recent study using a comparable task did not corroborate these earlier findings, but people with LBP were somewhat behind rather than in front of the targeted path and a relation to fear was noticed (Alsubaie et al., 2021). Eventually it remains unclear, whether interventions relying on similar tasks and setups could benefit people with LBP and how practicing such tasks affect the motor system. Therefore we will investigate if a sensor-based intervention with the main functionality to deliver feedback on the movements of the lower back affects movement, in particular postural sway in people with LBP.

1.3.2 *Understanding the processes involved*

2) How does fear of movement affect the motor system in people with LBP?

LBP is characterized by many predisposing variables from different domains, but it may be possible to influence some of these variables by interventions (Parreira et al., 2018). Maher et al. (2017) link the hampered effectiveness of today's interventions to the inability to locate and attend to the origin of LBP itself and Van Dieën et al. (2017) argue similarly to stress the significance of investigating motor control adaptations. Thus, clarifying how different variables are involved, and improving the understanding of relevant mechanisms in general, will enable the identification of parameters that can be adjusted, and ultimately facilitate the design of effective interventions. This also includes the question how fear of movement affects movement behavior in people with LBP.

> *"Evidence suggests that fear avoidance beliefs are prog-nostic [sic] for poor outcome in patients with subacute LBP and should be addressed in this population to avoid delayed recovery."*(Wertli et al., 2014, p.835)

This statement cited from a literature review highlights the importance which is ascribed to fears in people with LBP. In people with LBP and greater fear a rather stiff manner of moving was verified by a meta-analysis (Christe et al., 2021). However, fear explained only a minor portion of the variability (Christe et al., 2021). The discussion about the role of individual movements in the assessment of fear of movement had already started much earlier (Leeuw et al., 2007; Pincus et al., 2010), but either way, a weakness in the underlying literature was that fear of movement was predominantly assessed in a broader sense and not in connection to the concrete, investigated movement behaviors which could have affected the data (Christe et al., 2021).

Fear and postural balance during simple standing on two legs in people with LBP has been investigated before (Kahraman et al., 2018; Shanbehzadeh et al., 2018; Zhang et al., 2020). However, the obtained results differ. Kahraman (2018) detected no relation of the Tampa Scale of Kinesiophobia and velocity measures for different vision and surface manipulations, but a positive relation with a value that seems to be an aggregate across these manipulations in men. On the contrary, in the study of Shanbehzadeh et al. (2018) people with LBP and more intense fear displayed a reduction in sway relative to people with LBP and less fear, which was interpreted as a more rigid movement pattern accompanying fear. However, this result was shown as an aggregate comprising assessments with different manipulations. Zhang et al. (2020) showed a dependency of sway and catastrophic thoughts in people with LBP, albeit the reporting of the direction of the effect appears to be inconsistent in the manuscript. Although data for different directions of sway has been presented, e.g. in the study of Shanbehzadeh et al. (Shanbehzadeh et al., 2018), to our knowledge fear of different movement directions has not been explored in relation to balance.

1.3.3 *Technology in tracking risk factors*

3) Can high physiological strain in skiing athletes be quantified using sensors in smartphones?

For back health, an intermediate degree of physical activity is favorable (Alzahrani et al., 2019; Heneweer et al., 2009), but for example in a context of professions with higher physical work components, increases in physical activity might imply a greater likelihood to experience LBP (Øverås et al., 2020). Also the amount of health complaints including LBP in adolescent skiers are interpreted as fairly high and it was suspected that the active ski training may inflict many injuries (Schoeb et al., 2020). With imaging methods changes in the lower back have been observed in this population (Peterhans et al., 2020).

If risk factors, for instance the amount of ski training are continuously assessed, early interventions to reduce this risk may be possible. It has been suggested that sensor-based tracking could support athletes trying to avert the development of health issues developing due to intense sport practice (Düking et al., 2017). Contrasting subjective training information with data extracted from sensors hidden in the training material, it was found that data from these sources deviate sometimes vastly (Nicolson et al., 2018). Although this study (Nicolson et al., 2018) referred to a rehabilitation setting with people who had knee problems, ski training data derived from sensors could also be more accurate than data from manual diary methods.

A review showed that sensor-based descriptions of skiing mechanics have indeed been used in diverse studies (Supej and Holmberg, 2021). The authors predicted that in addition sensors from smartphones will be increasingly used in this field (Supej and Holmberg, 2021), but we are not aware of any studies using smartphone based apps to monitor training load in skiing athletes.

1.4 contributions

The work presented in this thesis centers on LBP and possible benefits of sensor-based tools to understand and manage LBP. Within the scope of this thesis it is only possible to investigate individual facets of this extensive field, therefore we spotlight three distinct aspects.

- Sensor-based intervention: The literature on exercising with digital and sensor-based tools for people with LBP suggests that only little evidence exists for many categories of tools (Matheve et al., 2017).

  Therefore, we have **1)** planned and conducted a RCT which combined different sensor-based intervention and tracking technologies in the field with laboratory based assessments. This RCT showed that **2)** an exergame with feedback on torso movements from IMUs does not improve postural sway, motor control, pain intensity, disability, quality of life or fear of movement. To our knowledge, this was the first intervention study investigating the effect of applications with feedback on torso movements on postural balance. **3)** We have investigated adherence to technology during largely self-directed use. **4)** The observation of higher adherence in an intervention period with predefined exercise schedule suggests that providing a training plan could improve adherence to the intervention, but this assumption should be tested in future studies.

- Understand the role of Fear in postural balance: There have been speculations about the relation of fear and postural balance regulation in people with LBP (Kiers et al., 2015; Mazaheri et al., 2013), but only few studies are available that assessed balance during regular standing on both legs. Shanbehzadeh (2018) found less spatial expansion and velocity of sway in people with elevated fears in comparison to less fearful people. On the other hand, Kahraman et al. (2018) found no association of fear and velocity during quiet bipedal standing, except for a positive association with one out of five measures and only for men. Further, the literature implies that for understanding the impact of fear on movement characteristics a more movement specific approach to fear assessment may be required (Pincus et al., 2010; Knechtle et al., 2021; Matheve et al., 2019; Christe et al., 2021).

In this study we found **1)** a positive association of COP velocity in the frontal plane with a general assessment of fear, but not the other sway parameters, adding to the accumulating evidence. The results from an analysis differentiating between fear of different directions of torso movements showed that **2)** fear of frontal plane movements may be more relevant to postural balance than fear of sagittal plane movements. **3)** We propose and show first data that whether movements in the frontal plane or sagittal plane elicit more fear might be relevant to postural balance, independently of the overall level of fear.

- Assessment of risk factors: A fair degree of physical activity seems to be ideal with respect to LBP, while insufficient and extraordinary high activity are connected to an elevated chance of LBP (Heneweer et al., 2009). LBP is common already in adolescent ski athletes (Schoeb et al., 2020) and is presumably linked to strains that occur during the active ski training (Spörri et al., 2015; Spörri et al., 2017).

  1) We propose a concept for a sensor-based quantification of training load, which could enable a better handling of the amount of training and risk. **2)** We present exemplary data from a single athlete which was collected within a larger cohort study where we digitally acquired phone-based sensor data of 40 participants during the course of one skiing season. It is shown that even in a largely uncontrolled setting, without a defined position of the phone on the body skiing activity can be clearly visualized, and is suitable to estimate skiing activity down to the number of turns performed. **3)** A retrospective comparison of the collected self-reported and sensor-based data highlights the need for appropriate participant adherence for both modes of data collection.

1.5 THESIS OUTLINE

This thesis is organized in 5 chapters. Chapters 2-4 are based on manuscripts which address the three main research questions outlined above.

In **Chapter two** we present a RCT investigating the effects of sensor-based exercises on different variables in people with LBP. In this study we used a medical device with which the participants practiced controlled movements of their torso while receiving feedback on a screen. We concluded that this training did not improve postural balance, but future studies should investigate the impact on lifting movements in more detail and explore the role of scheduling methods on exercise adherence.

Chapter three describes secondary analyses of data collected within the RCT presented in the previous chapter. We investigated whether fear of movement has an impact on postural balance and whether the movement plane for which fear is expressed has a distinct impact on postural sway in the frontal and sagittal plane. We conclude that fear of movement on the frontal plane seems to play a larger role for sway in comparison to fear of sagittal plane movements. In general we observed a tendency towards increased sway for higher fear.

In **Chapter four** we propose that the amount of ski training in young athletes could be assessed using sensors in smartphones and used to manage training load before LBP develops. We present a case study based on a young athlete who provided longitudinal smartphone sensor data and self-reported data. We compare this data and suggest that sensor data could be used to monitor the duration and frequency of ski training, the number of runs performed, and even the turns during each run. We encourage the development of such a system and highlight challenges encountered.

In **Chapter five** we summarize and discuss the conclusions and limitations of our studies. We propose directions for future research with sensor-based mobile devices for LBP.

1.6 PUBLICATIONS

Chapter two to four in this thesis are based on three publications that are currently under review or about to be submitted.

(P1) **Meinke, Anita**; Peters, Rick; Knols, Ruud; Swanenburg, Jaap⋆; Karlen, Walter⋆. *Feedback on Trunk Movements from an Electronic Game to Improve Postural Balance in People With Unspecific Low Back Pain: A Pilot Randomized Controlled Trial*, *(under review in JMIR Serious Games)* [1]

(P2) **Meinke, Anita**; Maschio, Cinzia; Meier, Michael; Karlen, Walter⋆; Swanenburg, Jaap⋆. The Association of Fear of Movement and Postural Balance in People with Low Back Pain. *in preparation for submission*

(P3) Spörri, Jörg⋆; **Meinke, Anita**⋆; Brogli, Luzius; Schwab, Patrick; Karlen, Walter. Sensor-based monitoring of on-snow ski practice using mobile phones: Case study of a young competing ski athlete. *in preparation*

1 ⋆ Authors contributed equally

2 EFFECTS OF EXERCISING WITH SENSOR-BASED FEEDBACK

Wearable inertial measurement units can measure body movements and therefore give real-time feedback on performed exercise. Furthermore, the presentation of such feedback may improve the adherence to this exercise. In this chapter, we answer the question whether exercising with a sensor-based digital intervention improves postural balance in people suffering from LBP. Although no effects on postural balance was found, we cannot conclude that sensor-based exergames are not useful for LBP therapy.

For the RCT this chapter is based on, a study protocol has been published:
Meinke, Anita., Peters, Rick., Knols, Ruud., Karlen, Walter., Swanenburg, Jaap. (2021). Exergaming Using Postural Feedback From Wearable Sensors and Exercise Therapy to Improve Postural Balance in People With Non-specific Low Back Pain: Protocol for a Factorial Pilot Randomized Controlled Trial. *JMIR Research Protocols 10.8 (e26982)*

This chapter is based on the open-access publication:
Meinke, Anita; Peters, Rick; Knols, Ruud; Swanenburg, Jaap; Karlen, Walter. *Feedback on Trunk Movements from an Electronic Game to Improve Postural Balance in People With Nonspecific Low Back Pain: A Pilot Randomized Controlled Trial*, *(under review in JMIR Serious Games)*

I have planned and prepared this study, including the study protocol and good clinical practice documents. I managed the clinical trial while it was running, instructed and supervised the outcome assessors. Further tasks of mine were the recruitment and inclusion of study participants. During the study I acted as contact person for the study participant and provided the introduction to the training program. Further I analyzed the data and drafted the text presented here. I have received statistical guidance on the analysis. All of these tasks I did under the supervision of my coauthors. WK (Sponsor) and JS (Principal Investigator) initiated the study. RP, RK and JS were consulted as physiotherapists if eligibility could not be determined by simple questions. All authors have edited the manuscript and read and agreed to the publication of the final version.

We thank Ramon Glättli, Kim Graf, Cinzia Maschio, Adrian Stutz, Tina Wunderlin, and Katharina Zahoranszky who assisted with the outcome assessments. We further thank Prof. Oliver Distler for taking the role as a study physician and the participants who invested their time and provided the data. We also would like to thank Hocoma AG for loaning the VALEDO Pro used in the motor control assessments and Lars Lünenburger (Hocoma AG) for support in exporting exercise adherence data from the VALEDO app. We like to thank the Swiss National Science Foundation funding this study from project grant (167302) within the National Research Program 75 "Big Data". Lars Lünenburger (Hocoma AG) contributed to the writing of the grant proposal which funded this study and was administered by Walter Karlen.

2.1 ABSTRACT

Background: Postural balance is compromised in people with low back pain, possibly by changes in motor control of the trunk. Augmenting exercising interventions with sensor-based feedback on trunk posture and movements might improve postural balance in people with low back pain.
Objective: We hypothesized that exercising with feedback on trunk movements reduces sway in anterior-posterior direction during quiet standing in people with low back pain. Secondary outcomes were lumbar spine and hip movement assessed during a Box Lift and a Waiter Bow task, as well as participant reported outcomes. Adherence to the exercising intervention was also examined.
Methods: A randomized controlled trial was conducted with participants in the intervention group receiving unsupervised home exercises with visual feedback using the VALEDO Home, an exergame based on 2 inertial measurement units (IMU). The control group received no intervention. Outcomes were recorded by blinded staff during 4 visits (T1-T4) at the University Hospital Zurich. The intervention group performed 9 sessions of 20 minutes in the 3 weeks between T2 and T3 and were instructed to exercise at their own convenience between T3 and T4. Postural balance was assessed on a force platform. Lumbar spine and hip angles were obtained from 3 IMU. The assessments included pain intensity, disability, quality of life, and fear of movement questionnaires.
Results: Thirty-two participants with nonspecific low back pain completed the first assessment T1 and 27 participants were randomized at T2 (14 control, 13 intervention). Intention-to-treat analysis revealed no significant difference in change in anterior-posterior sway direction during the intervention period with a specified schedule (T2-T3) between the groups (W=99, P=.36, r=.07). None of the outcomes showed significant change in accordance with our hypotheses. The intervention group completed a median of 61% exercises (range 2%; -99%) of the predefined training program. Adherence was higher in the first intervention period with a specified schedule.
Conclusions: The intervention had no significant effect on postural balance or other outcomes, but the wide range of adherence and a limited sample size challenge the robustness of these conclusions.

Trial Registration: ClinicalTrials.gov NCT04364243
Keywords: Low back pain, postural balance, exergame, postural feedback, motor control, kinesiophobia, inertial measurement unit, randomized controlled trial

2.2 INTRODUCTION

Low back pain (LBP) was the condition that contributed in 1990 as in 2017 the largest amount of years lived with disability to the global burden of disease (Wu et al., 2020). The impact of LBP ranges from causing minor inconvenience to substantial restrictions in daily activities, and in extreme cases disability and early retirement. Although there might be improvements when taking into account population age, the overall amount of years lived with disability from LBP was rising and needs to be addressed (Wu et al., 2020). Standard treatment recommendations for LBP often incorporate exercising and advice regarding physical activity (Lin et al., 2020) and it has been demonstrated that exercises for chronic LBP improve outcomes such as pain or disability to a certain degree (Hayden et al., 2005; Saragiotto et al., 2016; Middelkoop et al., 2010). Differences in effects between exercises with a distinct training focus have been appraised as negligible (Saragiotto et al., 2016; Middelkoop et al., 2010). The limited effectiveness motivates the exploration of new ways for enhancing these treatments, as it has already been outlined by other authors (Matheve et al., 2018b). Considering that changes of motor control of the lumbar region are discussed as a plausible cause for recurrence of LBP (Dieën et al., 2019), and given that feedback plays a central role in motor learning (Schmidt et al., 2019), digital tools that make movement patterns more visible, could be one such way to enhance exercise treatments. These interventions could be used together with other treatments as it was implemented in some previous studies (Hügli et al., 2015; Kent et al., 2015; Matheve et al., 2018b; Magnusson et al., 2008) or could be used independently as-needed as a form of self-management. Many people with LBP do not request treatment, especially those with mild disability (Ferreira et al., 2010). Supportive technology that can provide some degree of guidance at home while maintaining the independence of the individual user, could therefore be especially interesting for this group of people.

Motor control can be described *"... as the way in which the nervous system controls posture and movement to perform a specific mo-tor task, and includes consideration of all the associated motor, sensory, and integrative processes"* (Dieën et al., 2019, p.370). Physical characteristics and movement behaviors assessed to derive insights into deviations that occur in people with LBP concerning these processes have revealed many differences that still demand further clarification (Dieën et al., 2019). As an example for movement differences, limitations in range of motion (ROM) of the lumbar spine were found on all movement planes (Laird et al., 2014) and limited ROM of the trunk in the frontal plane but not on the sagittal plane seems to precede the occurrence of LBP (Sadler et al., 2017). Differences in the trunk region are thought to relate to differences in postural balance (Dieën et al., 2019), which have been found by many studies (Berenshteyn et al., 2019; Mazaheri et al., 2013; Ruhe et al., 2011). Consequently, practicing movement tasks that focus on movement of the lumbar spine and hip could have the potential to enhance postural balance. Nevertheless, as highlighted above the effects of LBP on movement behavior has been only in part untangled yet (Dieën et al., 2019).

Altered movement behaviors seem to further extend to tracing tasks, which work with feedback on trunk movements and have been used as an indicator for motor control in laboratory settings (Alsubaie et al., 2021; Willigenburg et al., 2013). These studies used tasks that required tracing a circular pattern (Willigenburg et al., 2013) or performing flexion movements (Alsubaie et al., 2021) with their trunk, while receiving concurrent feedback. Results regarding the accuracy were conflicting, as one study (Willigenburg et al., 2013) found a difference between people with and without LBP in the accuracy of the tracing, while the other did not (Alsubaie et al., 2021). However, the latter study (Alsubaie et al., 2021) confirmed differences with respect to timing relative to the feedback between the groups. Such findings suggest that similar tasks may serve not only as a proxy measure of trunk motor control, but also as training opportunity. It was recently found that practice to keep the lumbar spine constantly neutral during a box lift task was more successful, when participants obtained digital feedback than when the participants used a mirror (Matheve et al., 2018a). As mechanisms behind tracing errors proprioceptive acuity (Willigenburg et al., 2013) and stiffness (Alsubaie et al., 2021) have been suspected, although assumptions regarding stiffness were not supported by the data (Alsubaie et al., 2021).

The effects of exercising interventions on postural balance have been studied previously. Meta-analyses on intervention studies including elderly people suggest, that balance training (Low et al., 2017) and Pilates (Casonatto and Yamacita, 2020), but not programs focusing on strength or mixing different kinds of exercises (Low et al., 2017) can enhance postural balance. Multiple interventional studies with people with LBP found an impact of exercising interventions on at least one of the investigated criteria describing balance (Areeudomwong and Buttagat, 2019; Gholami Borujeni and Yalfani, 2019; Lomond et al., 2014), while in another study no differences in postural balance were detected (McCaskey et al., 2018). However, different tasks with varying requirements were used, as for example standing on moving ground (Lomond et al., 2014), standing on a single leg (Areeudomwong and Buttagat, 2019) and assessments in squat positions (Gholami Borujeni and Yalfani, 2019).

Digital tools for exercising (Matheve et al., 2017) and virtual reality applications (Bordeleau et al., 2021) have been investigated in people with LBP. Among the many diverse applications, which includes games available on the market as for example exercising with the well-known Wii balance board (Nintendo of America Inc., Redmond, WA, USA) (Kim et al., 2014; Zadro et al., 2019). Sensor technology has also been used to intervene on movement characteristics of the trunk in particular, for example in studies (Ribeiro et al., 2014; Ribeiro et al., 2020) where warning participants from extreme back movements during everyday work was investigated. On the other hand interventions have specifically encouraged movement of the lumbar spine in an exercising context (Hügli et al., 2015; Magnusson et al., 2008; Thomas et al., 2016) or are otherwise dedicated to providing feedback on lumbar spine movement (Hügli et al., 2015; Kent et al., 2015; Magnusson et al., 2008). For different kinds of tools there is yet only a small amount of research (Matheve et al., 2017). Therefore, such digitally supported training modalities should further be investigated. Different systems and technological setups have been explored, for instance cameras (Ciabattoni et al., 2016), wearable sensors (Matheve et al., 2018b), and sensors readily available in mobile phones in combination with virtual reality headsets (Alazba et al., 2019). Yet only few studies provide first insights in the effects of these interventions on movement quality in people with LBP (Hügli et al., 2015; Kent et al., 2015; Magnusson et al., 2008). One study suggested the intervention might have positively affected trunk range of motion (ROM), but it remains ambiguous whether there was a significant difference to the standard care control group (Magnusson et al., 2008). In another study no effect on ROM was found (Kent et al., 2015). Motor control impairment was not different in a study, were patients in the intervention group received access to additional exercises with sensor-based feedback other than the control group (Hügli et al., 2015). To our knowledge, the effect of such exercises on postural balance in people with LBP has not yet been investigated.

The primary aim of this study was to examine, if exercising with feedback on trunk movements can enhance postural balance, indicated by the change between the assessments prior and after the intervention in anterior-posterior (AP) postural sway. As secondary outcomes, movement of of the lumbar spine and hip during two different motor tasks and participant reported outcomes were included. Additional parameters to quantify postural balance were explored. A further aim was to analyze adherence to the intervention.

2.3 METHODS

The completed CONSORT-EHEALTH checklist is attached as Multimedia Appendix 1. The intervention was described according to the template for intervention description and replication checklist (TIDieR) (TIDieR) (Hoffmann et al., 2014).

2.3.1 *Study design*

This manuscript was based on a protocol (Meinke et al., 2021) that included an additional research question, which we could not address due to insufficient enrolment of an additional group including patients recruited from the University Hospital Zurich (UHZ) who received a standard exercise treatment. This setup was intended to enable a comparison of the effect of the intervention between those groups. To not expand this manuscript further, we focus on reporting methods relevant to the research questions that could be investigated based on the collected data. Other methods can be obtained from the published study protocol (Meinke et al., 2021) describing the original design.

The study design as relevant for this manuscript is a two-arm randomized controlled trial. Figure 2.1 shows the assessment and intervention schedule. The study took place at the UHZ, Zurich, Switzerland between May 2019, and October 2020. Except for an extension of the study period of 3 Months to compensate for a pause due to the COVID-19 pandemic, the study ended as planned, interim analyses of intervention effects were not conducted. Outcomes were assessed twice at T1 and T2, before an intervention was given. After another 3-week period with a fixed exercising schedule for the intervention group (T3) and a subsequent six weeks period without specified exercising schedule (T4) further assessments were taken. Participants were randomized during the assessments at T2 and those assigned to the intervention group received an introduction to the exercising program right after the assessment. After T3, participants in the intervention group kept the VALEDO Home exercising system (Hocoma AG, Volketswil Switzerland) at home, without being required to follow a specific schedule or to complete any exercises at all. This period was introduced to observe further adherence to the exercising program, without commitment to a schedule provided from a therapist or to complete for research purposes. Participants who were randomized to the control group did not receive a sham intervention. Use of pain medication during the study period were not recorded.
Block randomization with blocks of two and four, stratification by body height and 1:1 allocation was implemented through the randomization tool in RedCap (Harris et al., 2009) hosted at ETH Zurich. AM generated random sequences with the dedicated R package blockrand version 1.3 (Snow, 2013) and randomized the participants using RedCap. Staff conducting assessments of the outcomes was blinded and randomization occurred as late as possible (at T2) to reduce the risk of accidental unblinding.

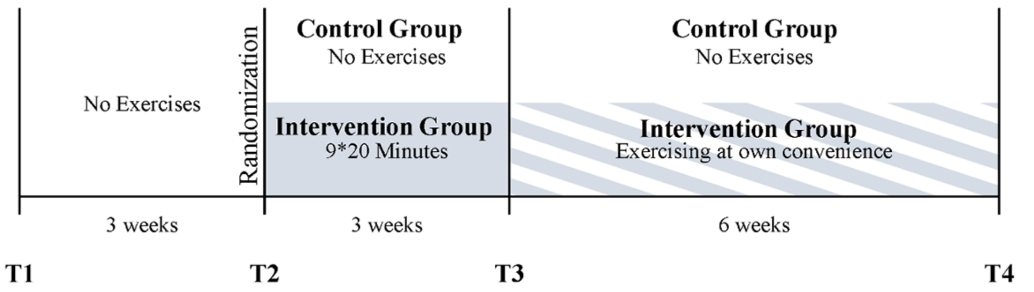

Figure 2.1: Schedule showing the assessment visits T1-T4 and interventions for both groups.

2.3.2 *Participant recruitment*

Participants were recruited through different online- bulletin boards, websites, distribution of flyers and personal communication. Recruitment ended 3 months before the planned end date, to allow all participants to finish in time. Eligibility was ascertained in an interview like setting that allowed the participants for example to indicate the painful area by pointing. There was no questionnaire-based assessment or formalized cutoff scores for pain intensity during the eligibility check. Participants were considered eligible after informed consent was provided, if they were at least 18 years old, confirmed nonspecific LBP and did not receive therapy or medical treatment for LBP within the past six months. The criterion of no recent treatment was relaxed from 12 months to six months during the study to improve low recruitment rates. Participants reporting specific LBP or radicular syndrome were excluded from participation. Participants were excluded if they indicated to the investigator that they would not be able to compete the movements required by the exercise intervention due to high pain. Other reasons for exclusion were pregnancy, taking medication that impairs postural balance, severely impaired vision, allergic reactions to adhesive strips and insufficient proficiency in German or English language.

Participants were not compensated for their participation and provided informed consent in writing prior to any study procedure. The trial was approved by the Cantonal Ethics Committee Zurich (BASEC: 2018-02132) and registered in ClinicalTrials.gov (NCT04364243).

2.3.3 *Outcomes and procedures*

2.3.3.1 *Postural Balance*

Records of center of pressure (COP) during quiet standing on a stable force platform (AMTI, Accusway Plus, Watertown, MA, USA) were used to quantify postural balance. Specifications of the number of repetitions, duration, instructions, sampling rate and filter cut-off frequency were based on relevant literature (Ruhe et al., 2010) and are described in detail below. During the assessment the participants stood as quietly as they could (Ruhe et al., 2010), with the arms relaxed at the side and eyes closed while wearing opaque goggles. Each participant selected an individually comfortable, "usual" foot position. To keep the stance consistent for each participant during all balance assessments, the foot position was recorded on a plastic foil. Participants wore socks but no shoes on the platform. Four postural balance trials of 120 s were recorded with a sampling rate of 100 Hz at each assessment visit. The data were filtered using a fourth order low-pass Butterworth filter with a cut-off frequency of 10 Hz. The first and last 5 s were removed from the records, to permit a stabilization phase at the beginning and assure that any effects of the sideways leaning movement for time synchronization were removed with a safety margin. Thus, parameter estimates for each repetition were based on segments of 110 s. The trajectory of the COP was described by the mean absolute displacement from the mean center of pressure (global), in anterior-posterior (AP) and medio-lateral (ML) direction as well as by corresponding velocities (Prieto et al., 1996). Change in displacement in AP direction (T3-T2) was a priori defined as the primary outcome. The data were reported on a mm and mm/s scale, reduction in displacement and velocity were the favorable outcome.

2.3.3.2 *Movement tasks*

Further assessments during movement tasks were performed to see whether the participants were able to follow the instructions to limit movement of the lumbar spine and perform movements on the sagittal plane by bending the hip joint instead. The protocol and setup of these assessments was adopted from Matheve and colleagues (Matheve et al., 2018c), where a Box Lift and a Waiter Bow task were shown to be reliable. Similar versions of these tasks have been used elsewhere (Matheve et al., 2018a). Figure 2.2 shows the setting and adaptation of the tasks to the individual participants, which were also adopted from other Matheve and colleagues (Matheve et al., 2018c). Lumbar spine and hip angles during the tasks were used to describe the performance during these tasks. During the Waiter Bow task participants should keep their knees in the original position. The VALEDO Pro (Hocoma AG, Volketswil Switzerland), consisting of 3 Inertial Measurement Units (IMU) and dedicated software was used for the assessments. Two IMUs were placed with medical adhesive strips at the height of the spinal process of the S1 and L1 vertebrae. One IMU was placed at the left leg, 20 cm from the lateral femoral condyle. Sensor positions were identified by palpation. Different than in the study mentioned above (Matheve et al., 2018c), we did not alter the participants natural spinal posture before the tasks were performed as we assumed the tasks would be selectively more difficult to perform for participants who received more intense corrections to their posture. In addition, we allowed only 1 practice trial before the 5 repetitions of each task to keep learning effects minimal. By tracing the position of the feet to a foil the position was standardized across assessments.

The Box Lift task required the participants to lift a box and hold it during upright standing, put the box down again and return to the standing position. For the Waiter Bow task, the participants were asked to touch a marked spot positioned in front of them with the fingers by bending from the hip joints and come back into upright stance. The central instruction was to not change the alignment of the lumbar spine when performing the tasks. Participants stood with parallel feet at self-selected width, in a predefined distance to the task materials. Correct task execution and possible mistakes were shown to the participants by the outcome assessor. The order of tasks was randomized for each assessment visit. The data were collected at a sampling frequency of 50 Hz and change in lumbar spine angle was calculated by subtracting the rotation of the S1 sensor on the sagittal plane from the rotation of the L1 sensor on the sagittal plane. The obtained data were filtered using a moving average of 0.2 s and the maximum absolute departure of the position at task beginning was used as endpoint. Hip angles were obtained analogously using data from the IMU at S1 and the IMU at the thigh.

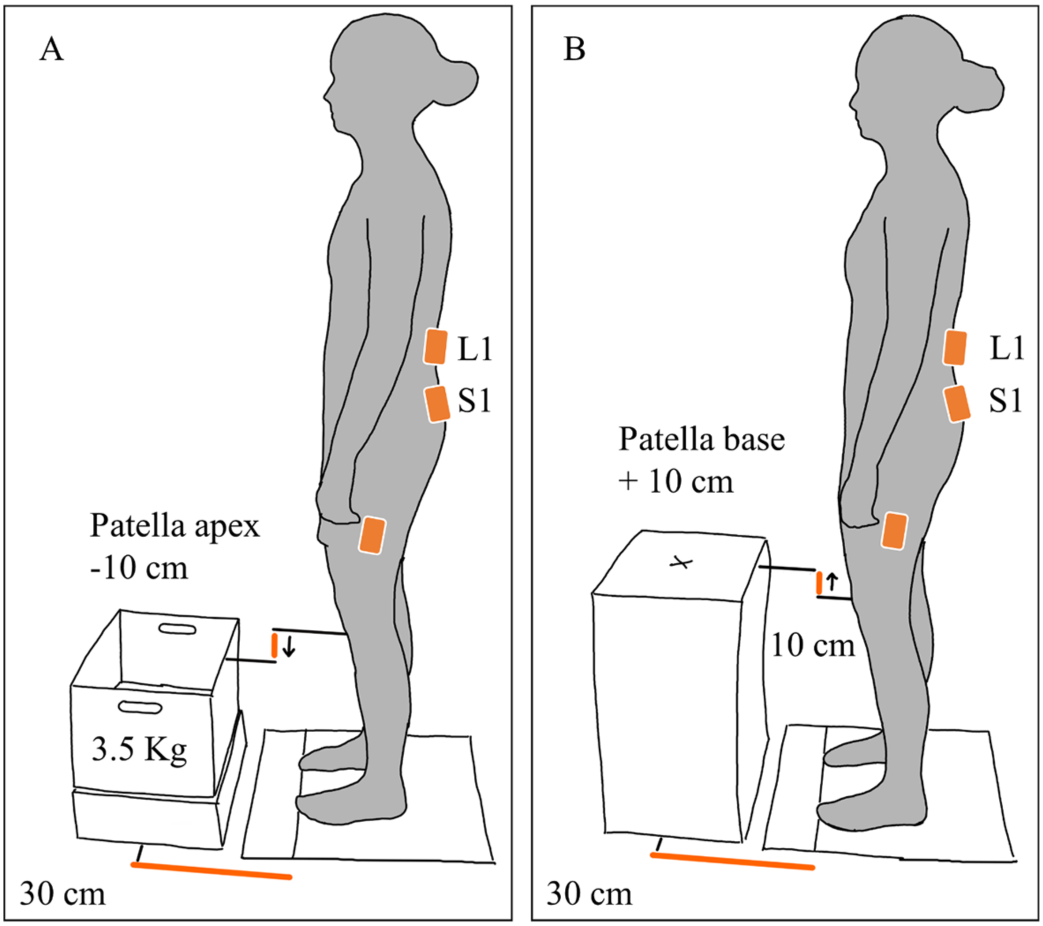

Figure 2.2: Setup of the movement tasks, IMU positions (orange markers), and task adaptation for A: Box Lift task, B: Waiter Bow Task.

2.3.3.3 *Participant reported outcomes*

Before the movement assessment at each visit, the participants completed a questionnaire in English or German language on a laptop. Considering the recommendations regarding relevant outcome assessments for studies on LBP (Chiarotto et al., 2015) we included questionnaires covering pain intensity, disability associated with LBP and quality of life (QOL). An 11-point Numeric Rating Scale (NRS) asking participants to rate their pain intensity during the previous week with the anchors no pain and worst imaginable pain was included (Chiarotto et al., 2018).
The Roland Morris disability questionnaire (RMDQ) was used to measure disability (Roland and Morris, 1983; Wiesinger et al., 1999). Respondents selected those of 24

statements which they experienced on the date of assessment, resulting in scores from 0 to 24 (Roland and Morris, 1983; Wiesinger et al., 1999). The RMDQ is an established questionnaire with adequate psychometric performance (Chiarotto et al., 2020).
The World Health Organization Quality of Life Questionnaire (WHOQOL-Bref) includes 26 items, which cover different aspects of QOL: physical health, psychological QOL, social relationships and environmental factors (Whoqol Group, 1998). The score of the physical health subscale is calculated by averaging the responses of 7 items (5 response options per item, multiplied by 4) (Whoqol Group, 1998). The selection of questions for the WHOQOL-Bref was based on data from international samples (Whoqol Group, 1998) and was found to be reliable and valid (Whoqol Group, 1998; Skevington et al., 2004).
The 11 item Tampa Scale for Kinesiophobia (TSK-11) was used to measure fear of movement and the sum scores (4 response options, 11 to 44) were analyzed (Woby et al., 2005; Rusu et al., 2014). The English and German versions were found to generate reliable and valid data (Woby et al., 2005; Rusu et al., 2014).

2.3.3.4 *Baseline characteristics and adherence*

The questionnaire at T1 included questions regarding the participants age at the first occurrence of LBP, days with LBP during the previous month and , the average LBP intensity (When you have back pain, how would you rate your average low back pain intensity in general?) using labels of no pain and worst imaginable pain to describe the minimum and maximum values of 0 and 10. In addition, demographic data were collected. Weight and height were assessed on site. The exercises that were performed at home and the matching timestamps were extracted from the VALEDO Home app.

2.3.4 *Intervention*

The intervention is described in Table 2.1. A Graph showing an info-graphic on the intervention and the movements is reproduced from the study protocol (Meinke et al., 2021) in Figure 2.3.

Figure 2.3: Graphical display and movements of the exercise intervention. The graph is reproduced from Meinke et al. (2021).

Table 2.1: TIDieR checklist items (Hoffmann et al., 2014) for exercising with postural feedback.

Item	Intervention description

Brief Name:	Exercising with postural feedback on trunk movements using the VALEDO Home System.
Rationale:	Postural balance deficits in people with LBP may stem from disturbed coordination of the trunk. We assume that practicing trunk movements with a feedback system helps participants to learn to control their trunk more precisely. This improved control of the trunk could in turn affect how well balance can be controlled in people with LBP.
Materials:	The VALEDO home system (Hocoma AG, Volketswil, Switzerland) and belts or medical adhesive strips that were used for attaching the sensors to the chest and lower back. A Tablet (Huawei Media Pad T5) with the VALEDO app was provided, a paper document summarizing the instructions, and the user manual (HOCOMA AG, 2018).
Procedures:	Participants randomized to the intervention group were instructed how to use the VALEDO system and performed 1 exercise under supervision at T2. The research protocol (Meinke et al., 2021) includes a graphical descirption of the intervention. During this training the participants learned how to place the sensors correctly and to use the tablet and the VALEDO app. At each of 9 home exercising session, the participants did 10 exercises. Participants practice to move their trunk and pelvis precisely to guide an avatar along a specified path with their movements through a virtual world. The exercises consist of movements of the upper body or the pelvis. Trunk movements are performed on the sagittal, frontal and transversal plane, and hip movements are performed on the sagittal and frontal plane. Participants see on the display how well they match the specified movement trajectory while playing and further auditory feedback is provided. At the end of the game a ranking of the current and previous performance in the game is provided. After the assessment at T3 participants in the intervention group were informed that they could keep using the system until T4, but that there was no specific schedule to complete and they could use the system at their own convenience.
Provider:	The exercises were delivered by the VALEDO Home system. AM trained the participants and acted as contact person during the study. The participants were encouraged to contact AM if any questions or technical difficulties should occur.

Mode of delivery:	Each participant was instructed individually. Exercises were guided by the VALEDO Home system.
Location:	Instructions took place at the UHZ, the regular exercises were conducted by the participants at home.
Frequency and Amount:	The participants completed 10 exercises with an effective duration of 20 minutes repeatedly at 9 sessions until T3. Participants were told to space the exercising sessions approximately equally between the appointments, but exact dates were not defined. After T3 the participants could choose the exercises and duration by themselves.
Tailoring:	The exercises are adapted to the ROM of the participant, which is measured as part of the user profile setup. Participants could repeat this assessment at any time. Progress and difficulty were determined by the VALEDO Home app.
Modifications:	To improve the attractivity of the study and recruitment, starting September 2019 the participants in the control group could borrow the VALEDO Home and tablet for 3 weeks after completion of T4.
Adherence measures:	The exercises performed by the participants were automatically recorded on the tablet.
Actual adherence:	Reported in the results section.

2.3.5 *Data preparation and statistical analysis*

Data preparation and analysis were conducted in MATLAB R2018a (The MathWorks Inc., Natick, MA, USA) and R version 4.0.4 (R Foundation for Statistical Computing, Vienna, Austria). The simultaneously recorded data of the force platform and the IMUs was time-synchronized based on a sideways leaning movement of the participants, shifting their weight to the left and the right, that was performed before and after each repetition. This parallel recording was necessary for a follow-up project comparing force plate and IMU data. For time-synchronization the movement had to be clearly distinct from the tasks and to be identifiable in both sources of data. The beginning and the end of each balance and movement task were defined based on marker timestamps set on the IMU data during the assessment.

The markers were inspected visually and corrected by hand before further analysis, as placement during the assessment was sometimes not optimal but occurred too early during the time-synchronization movement or too late during the task. To assess the equivalence between the treatment groups at study entry (T1), participant characteristics were compared. Welch t test or alternatively Wilcoxon Rank Sum tests were used, if the data appeared to be not normally distributed based on Normal QQ plots or Shapiro-Wilk tests within groups. Dependent group t test were used to test if change had occurred between T1 and T2 or, if the assumptions were not met Yuen tests as provided by the R package WRS2 (Mair and Wilcox, 2020). The hypotheses regarding the intervention effects were tested by comparing the change of the respective outcome (Δ Outcome, $T3 - T2$) between the intervention and the control group, predicting the more favorable outcome for the intervention group. These comparisons were performed each as intention-to-treat (ITT) and per-protocol analyses (PP). In the ITT analyses, all participants who had been randomized at T2 were included. Missing values at T2 and T3 were replaced with the mean of the previous two assessments (T1, T2) of the participant. For the PP analyses participants were excluded, who either had incomplete data or had been randomized to the intervention group but exercised less than 1h between T2 and T3. Comparisons were performed using t tests, when the data was normally distributed according to Shapiro-Wilk tests and a Levene test did not show heterogeneity of variances, otherwise Wilcoxon Rank Sum Tests were used. Additional exploratory analyses to compare the absolute scores across all assessment visits including the second intervention period were conducted using mixed two-way ANOVA. Only participants who completed the study (n=20) were included in these analyses. Missing data were replaced by mean scores of the previous assessments of that participant. Generalized Eta Squared was used as an effect size (Bakeman, 2005) and calculations were made using the r package rstatix version 0.7.0 (Kassambara, 2021). Shapiro-Wilk tests and Levene tests were used to test the assumptions of normality and homogeneity of variances. Greenhouse-Geisser corrected P values are reported where the assumption of sphericity was violated. If the data did not fulfill the assumptions of normality and homogeneity of variances, different data transformations were explored. In cases were no suitable transformation was found, Friedman ANOVA was conducted across the assessment visits for each group separately and group differences were compared at each assessment visit using Bonferroni corrected Wilcoxon rank-sum tests. Data on adherence were analyzed using descriptive statistics and graphs.

2.4 Results

2.4.1 *Data cleaning*

Based on visual inspection, orientation data from the IMU sensors was corrected in two cases where axes where flipped (15 trials of 2 participants). The data from 1 participant at T1 and another participant in the control group at T2 was discarded, because misplacement of the sensors was suspected. For 1 participant in the intervention group no data for the T3 assessment was available, since the sensors had not been sufficiently charged. In the ITT analysis all participants randomized were analyzed and missing values replaced as described in the methods section. For the movement tasks 1 replacement in the control group was made for T2, and 7 replacements (5 control, 2 intervention) for the T3 assessments. For the ITT analysis of the balance and the questionnaire data 6 replacements (5 control, 1 intervention) were made for T3. For the per-protocol analysis participants for whom replacements had to be made were removed from the analysis. In addition, data of participants in the intervention group who had exercised less than 1h within the three-week period and were excluded from the per-protocol analysis, where this was not already the case if the participant was also a dropout or had been removed due to the insufficiently charged sensors (3 balance and questionnaires, 2 movement tasks). During data analysis it was discovered that some of the items of the WHOQOL–Bref at T3 in the German language version had been collected with response options ranging from 1 to 4 instead of 1 to 5. Data collected with the affected items (Items 3 to 9) were discarded for all assessment visits and the scores of the scales calculated without those items. As not all data fulfilled the requirements for two-way mixed ANOVA for the analysis across all 4 assessment visits, the data was transformed were necessary. Transformations applied are reported in Table 2.2. The effective duration between T1 and T2 was on a Median 21 days (IQR 5; Min=17; Max=97), between T2 and T3 23 days (IQR 3; Min=19; Max=36) and between T3 and T4 44 days (IQR 7.75; Min=38; Max=112). For one participant the time span between T1 and T2 was extended to 97 days and for two participants the period between T3 and T4 was extended to 112 and 99 days respectively because of an interruption in the study due to the COVID-19 pandemic. The period between T2 and T3 was not affected.

Table 2.2: Transformations applied to satisfy requirements for the analysis including all assessment visits in the two-way mixed ANOVA.

Outcome	Transformation
Mean anterior-posterior displacement	max(1/(x+1))-(1/(x+1))
Mean medio-lateral displacement	log(x+1)
Mean global displacement	log(x+1)
Mean anterior-posterior velocity	None necessary
Mean medio-lateral velocity	max(1/(x+1))-(1/(x+1))
Mean global velocity	None necessary
Box lift lumbar spine	log((x/5)+1)
Box lift hip	log((x/5)+1)
Waiter bow lumbar spine	log((x/5)+1)
Waiter bow hip	log((x/5)+1)
Pain intensity numeric rating scale	log(x+1)
Roland Morris disability questionnaire	No suitable found
Quality of life physical subscale	log(x+1)
Tampa scale of kinesiophobia -11 item version	None necessary

2.4.2 *Participants and baseline characteristics*

As presented in Figure 2.4, 93 participants made an initial contact and requested information regarding the study. Of those participants, 38 provided written informed consent. At T1, 32 participants without recent treatment for LBP were eligible for the study. Three patients enrolled into the study but were excluded from all analyses due to their small number. Five participants dropped out before randomization at T2 (n= 27). Table 2.3 shows the participant characteristics at baseline. Between participants randomized to the intervention and control group there were no significant differences in any outcome measure at T1 or T2, but analyses of change between T1 and T2 revealed that there was a significant reduction in pain intensity across participants who had been randomized (T1: median 3.00; mean 3.26, SD 1.56, T2: median 2.00; mean 2.59, SD 1.34). There was a slight, non-significant increase in ML displacement (T1: median 2.03; mean 2.28, SD 1.02, T2: median 2.47; mean 2.61, SD 1.31) and global displacement (T1: median 4.72; mean 5.35, SD 1.81; T2: median 5.24; mean 5.78, SD 1.99). Descriptive statistics on all outcomes at all assessment visits are reported in Table 2.5 and comparisons of outcomes at T1 and T2 are shown in Table 2.4.

Table 2.3: Participant characteristics at T1.

Characteristic	Control n=14 median, mean (SD)	Intervention n=13 median, mean (SD)	Comparison *P* Value
Gender [female/ male]	9/ 5	8/ 5	-
Age [years]	37.50, 40.14 (12.38)	34.00, 40.85 (15.15)	.92[a]
Height [cm]	174.25, 173.27 (8.61)	170.50, 170.73 (6.55)	.39
Weight [kg]	73.55, 76.01 (11.97)	74.10, 72.56 (9.57)	.41
Language [German/ English]	11/ 3	11/ 2	-
Age at first time LBP [years]	24.50, 26.50 (10.51)	20.00, 24.00 (9.52)	.52
LBP previous Month [days]	10.00, 9.43 (6.16)	11.00, 5.46 (10.08)	.16[a]
Average Pain Intensity [0-10]	4.00, 4.07 (1.33)	4.00, 3.85 (1.07)	.63

[a]. Comparison Wilcoxon rank-sum test.

Table 2.4: Comparison of outcomes of the randomized sample at T1 and T2 and between T1 and T2.

Outcome	T1		T2		T1 vs. T2	
	t(df)/ W	P	t(df)/ W	P	t(df)/ ty(df)	P
Displacement AP	120	.17[a]	0.77(23.28)	.45	-1.17(16)	.26[b]
Displacement ML	110	.38[a]	95	.87[a]	-1.77 (26)	.09
Displacement Global	116	.24[a]	0.79(24.37)	.44	-1.77 (26)	.09
Velocity AP	-1.38 (23.53)	.18	-1.60(24.57)	.12	-0.64(26)	.53
Velocity ML	83	.72[a]	84	.76[a]	-0.43(26)	.67
Velocity Global	-1.06 (24.55)	.30	-1.12(22.83)	.28	-0.64(26)	.53

LS Box Lifting	1.00 (24.46)	.33	101	.42[a]	-0.89(25)	.38
H Box Lifting	0.11 (24.58)	.91	95	.61[a]	1.01(25)	.32
LS Waiter's Bow	-0.23 (24.80)	.82	93	.69[a]	0.21(15)	.83[b]
H Waiter's Bow	83	.72[a]	69	.45[a]	-1.18(25)	.25
NRS	-0.15 (22.95)	.88	-0.08(22.50)	.93	2.11(26)	.045
RMDQ	67.5	.26[a]	87	.86[a]	1.53(16)	.15[b]
QOL- Physical	94.5	.88[a]	98.5	.73[a]	1.15(16)	.27[b]
QOL- Psychological	0.03 (24.99)	.98	106.5	.46[a]	-0.25(16)	.81[b]
QOL- Social	101	.64[a]	0.17(24.77)	.87	0(16)	.99[b]
QOL- Environment	-0.23 (24.02)	.82	91.5	1.00[a]	0.13(16)	.90[b]
TSK-11	-1.18 (24.96)	.25	-1.13(23.66)	.27	-0.29(26)	.77

a Comparison Wilcoxon rank-sum test.

b Comparison Yuen Test.

2.4.3 *Change in outcomes during the intervention period with predefined schedule*

The change in the outcome variables between (T3-T2) was compared between both groups, for all outcome variables. All comparisons were performed as ITT and PP analyses. Intention to treat analyses were performed with 14 participants in the control and 13 participants in the intervention group, as randomized. Per Protocol analyses were conducted with 9 participants in each group, except for the movement tasks, where only data of 8 participants was available in the control group.

2.4.3.1 *Postural balance*

The primary outcome, change between T2 and T3 in mean AP displacement, did not differ between groups in the ITT analysis (Control: median -0.01; mean -0.32, SD 0.95, Intervention: median -0.18; mean -0.31, SD 0.77, Comparison: W=99; P=.36; r=0.07) and neither in the PP analysis (Control: median -0.03; mean -0.45, SD 1.17, Intervention: median 0.05; mean -0.17, SD 0.69, Comparison: t_{16}=0.64 P=.73; r=0.16). In addition, no group differences in the ITT or PP analyses were found for

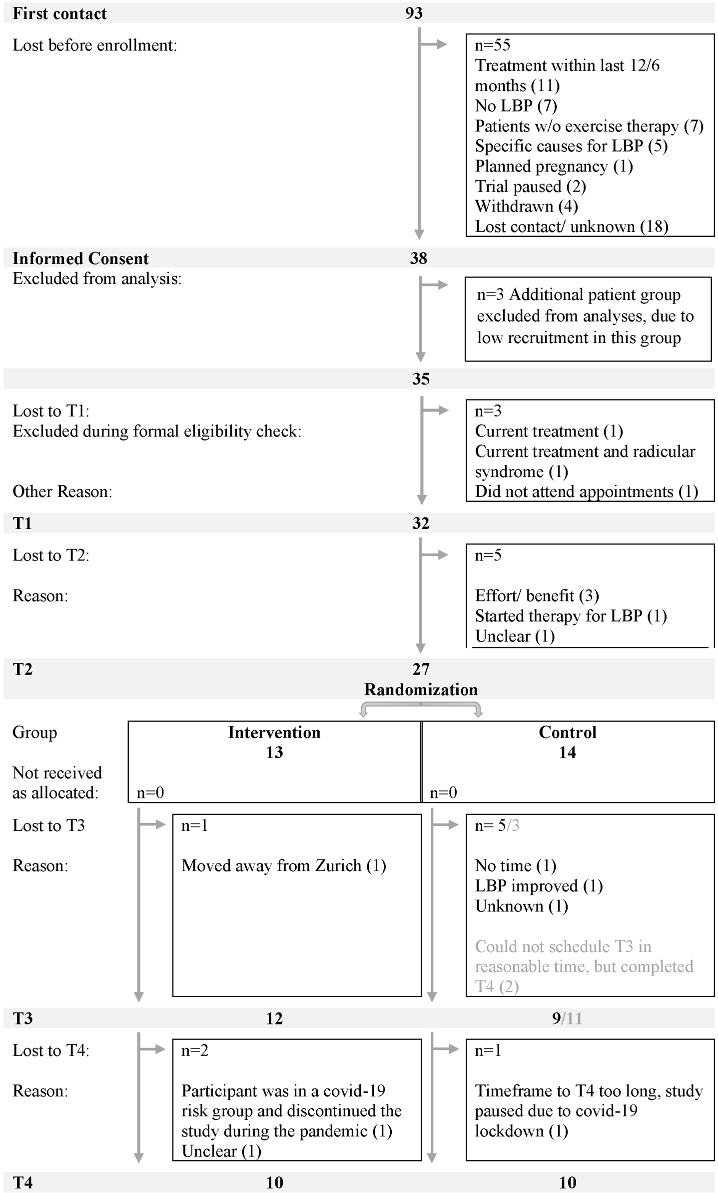

Figure 2.4: Participant flow through the study. Numbers of analyzed participants are reported in the text.

the other postural balance parameters explored, Δ COP displacement in ML and global direction and Δ COP velocity in AP, ML, or global direction (Table).

Table 2.5: Descriptive statistics of outcome measures at each assessment visit.

Outcome	Control median, mean (SD)	Intervention median, mean (SD)
Assessment Visit T1		
n	14	13
Displacement AP	4.27, 4.68 (1.59)	3.72, 3.97 (1.01)
Displacement ML	2.16, 2.46 (1.19)	1.97, 2.08 (0.80)
Displacement Global	5.26, 5.78 (2.10)	4.62, 4.89 (1.38)
Velocity AP	7.70, 8.62 (2.33)	9.96, 10.00 (2.78)
Velocity ML	3.54, 3.97 (1.66)	3.57, 3.99 (1.33)
Velocity Global	9.69, 10.31 (2.92)	11.19, 11.54 (3.10)
Lumbar Spine Box Lifting	17.46, 19.68 (11.55)	14.20, 15.68 (9.19)
Hip Box Lifting	83.51, 85.13 (16.58)	80.57, 84.42 (17.49)
Lumbar Spine Waiter Bow	12.43, 14.32 (8.77)	13.26, 15.10 (8.89)
Hip Waiter Bow	16.41, 21.06 (12.14)	18.86, 21.39 (13.45)
NRS	3.00, 3.21 (1.85)	3.00, 3.31 (1.25)
RMDQ	1.50, 2.57 (2.85)	3.00, 3.15 (1.86)
QOL Physical	4.14, 4.11 (0.61)	4.14, 3.99 (0.75)
QOL Psychological	4.00, 3.92 (0.71)	4.00, 4.01 (0.58)
QOL Social	4.00, 3.95 (0.85)	4.00, 3.90 (0.64)
QOL Environment	4.06, 4.18 (0.55)	4.25, 4.25 (0.55)
TSK-11	18.00, 18.79 (4.61)	22.00, 20.85 (4.45)
Assessment Visit T2		
n	14(13 Motor control tasks)	13
Displacement AP	4.86, 4.72 (1.65)	3.94, 4.41 (1.34)
Displacement ML	2.39, 2.80 (1.52)	2.47, 2.41 (1.06)
Displacement Global	5.40, 6.07 (2.22)	4.89, 5.46 (1.74)
Velocity AP	8.88, 8.84 (2.38)	9.87, 10.17 (1.92)
Velocity ML	3.68, 4.10 (1.91)	3.77, 4.02 (1.26)
Velocity Global	10.15, 10.59 (3.15)	11.43, 11.74 (2.11)

Lumbar Spine Box Lifting	18.39, 21.12 (10.73)	14.07, 18.75 (13.21)
Hip Box Lifting	90.27, 84.19 (14.45)	77.57, 81.72 (18.78)
Lumbar Spine Waiter Bow	11.11, 15.30 (8.23)	10.47, 15.11 (11.64)
Hip Waiter Bow	19.62, 21.79 (9.58)	23.26, 24.78 (13.41)
NRS	2.00, 2.57 (1.60)	3.00, 2.62 (1.04)
RMDQ	1.00, 2.71 (3.47)	2.00, 2.31 (2.02)
QOL Physical	4.21, 4.02 (0.74)	3.86, 3.92 (0.75)
QOL Psychological	4.00, 3.88 (0.76)	4.00, 3.79 (0.89)
QOL Social	3.83, 3.90 (0.88)	4.00, 3.85 (0.90)
QOL Environment	4.19, 4.06 (0.68)	4.00, 3.96 (1.05)
TSK-11	19.00, 18.79 (5.13)	20.00, 21.23 (6.04)
Assessment Visit T3		
n	9	12 (11 Motor control tasks)
Displacement AP	3.90, 4.18 (0.83)	3.86, 4.13 (1.08)
Displacement ML	1.73, 2.21 (0.92)	1.89, 2.05 (0.89)
Displacement Global	5.03, 5.16 (1.16)	4.67, 5.03 (1.31)
Velocity AP	8.15, 8.02 (2.37)	9.40, 9.52 (2.68)
Velocity ML	3.32, 3.63 (1.35)	3.29, 3.86 (1.49)
Velocity Global	9.36, 9.53 (2.82)	10.88, 11.02 (3.11)
Lumbar Spine Box Lifting	14.36, 15.07 (8.89)	17.10, 19.79 (13.23)
Hip Box Lifting	82.52, 82.07 (18.60)	89.46, 84.28 (16.94)
Lumbar Spine Waiter Bow	11.51, 11.16 (5.62)	14.70, 16.88 (9.30)
Hip Waiter Bow	20.08, 24.27 (18.00)	21.96, 26.04 (13.97)
NRS	3.00, 2.88 (1.90)	2.00, 2.50 (1.57)
RMDQ	2.00, 2.44 (2.60)	1.50, 2.58 (3.18)
QOL Physical	4.14, 4.11 (0.61)	4.43, 4.05 (1.08)
QOL Psychological	3.83, 3.63 (0.78)	4.06, 3.94 (1.01)
QOL Social	4.00, 3.96 (0.54)	4.00, 3.86 (1.06)
QOL Environment	4.25, 4.29 (0.32)	4.38, 4.21 (0.96)
TSK-11	18.00, 19.33 (4.97)	21.00, 20.25 (6.34)

Assessment Visit T4		
n	10	10
Displacement AP	4.44, 4.51 (1.67)	3.66, 3.78 (1.01)
Displacement ML	2.54, 2.59 (1.22)	2.02, 2.16 (1.09)
Displacement Global	5.51, 5.69 (2.16)	4.73, 4.76 (1.56)
Velocity AP	7.88, 8.33 (2.22)	9.09, 9.17 (1.76)
Velocity ML	3.35, 3.99 (1.83)	3.74, 3.79 (1.27)
Velocity Global	9.66, 10.05 (2.96)	11.17, 10.68 (1.90)
Lumbar Spine Box Lifting	15.01, 18.67 (12.57)	24.45, 23.66 (14.49)
Hip Box Lifting	86.09, 85.70 (14.10)	83.01, 79.51 (21.53)
Lumbar Spine Waiter Bow	13.13, 13.46 (8.55)	18.76, 17.46 (9.18)
Hip Waiter Bow	20.85, 22.35 (8.72)	23.67, 25.05 (14.77)
NRS	3.00, 3.20 (1.03)	2.00, 2.30 (1.49)
RMDQ	2.50, 3.40 (2.95)	1.50, 2.10 (2.51)
QOL Physical	4.00, 3.96 (0.84)	4.36, 4.01 (0.92)
QOL Psychological	4.17, 3.92 (0.78)	3.92, 3.92 (0.69)
QOL Social	4.00, 3.80 (0.82)	4.00, 3.73 (1.12)
QOL Environment	4.06, 4.05 (0.71)	4.50, 4.30 (0.60)
TSK-11	20.50, 20.10 (4.84)	17.00, 18.50 (4.90)

2.4.3.2 *Movement Tasks*

Comparisons of change between T2 and T3 in Lumbar and Hip movement during the movement tasks are shown in Table 2.6 and Figure 2.5. There was no significant difference in either the ITT or the PP comparisons in accordance with our hypotheses. However, for the lumbar spine there were small decreases in the deviation from the starting position during task performance in the control group and small increases in the intervention group. Thus, the results showed a trend opposing our predictions with respect to the lumbar spine for both, the Box Lift and Waiter Bow task with moderate effect sizes.

Table 2.6: Directed group comparisons of change in motor control and participant reported outcomes between T2 and T3.

Analysis[a]	Control	Intervention	Comparison			
	median, mean (SD)	median, mean (SD)	b	t(df)/W	P	r
Δ Box Lift Lumbar Spine						
ITT	-3.05, -3.00 (8.61)	3.37, 3.25 (12.10)	-1.56(25)	.93	0.30	
PP	-5.37, -5.05 (10.31)	6.69, 6.03 (13.00)	-1.93(15)	.96	0.45	
Δ Box Lift Hip						
ITT	0.31, -0.14 (8.52)	1.10, 0.43 (12.04)	-0.14(25)	.44	0.03	
PP	2.48, 0.84 (10.21)	-2.27, -2.07 (12.11)	-0.53(15)	.70	0.14	
Δ Waiter Bow Lumbar Spine						
ITT	-1.12, -2.50 (5.22)	1.91, 3.16 (8.22)	-2.15(25)	.98	0.40	
PP	-1.12, -2.62 (5.51)	1.91, 3.07 (7.14)	-1.82(15)	.96	0.42	
Δ Waiter Bow Hip						
ITT	-0.85, 1.50 (6.83)	1.32, -0.48 (10.33)	92	.53[b]	0.01	
PP	-1.81, 2.46 (8.93)	1.32, 0.41 (7.94)	33	.41[b]	0.07	
Δ Pain Intensity Numeric Rating Scale						
ITT	0.00, 0.14 (1.18)	0.00, -0.12 (1.12)	0.58(25)	.28	0.12	
PP	0.00, 0.44 (1.33)	0.00, -0.44 (0.88)	1.67(16)	.06	0.38	
Δ Roland Morris Disability Questionnaire						
ITT	0.00, -0.25 (1.90)	0.00, 0.12 (2.26)	88	.57[b]	0.03	
PP	0.00, 0.33 (1.41)	-1.00, -0.55 (1.67)	1.22(16)	.12	0.29	
Δ Quality of Life- Physical Subscale						
ITT	0.20, 0.23 (1.83)	1.60, 1.11 (1.06)	63.5	.09[b]	0.26	
PP	1.60, 0.53 (2.23)	1.60, 1.60 (0.80)	27.5	.13[b]	0.27	
Δ Tampa Scale of Kinesiophobia -11 item version						
ITT	-0.75, -0.04 (2.63)	-1.00, -0.88 (3.18)	0.76(25)	.23	0.15	
PP	-1.00, 0.11 (3.18)	-1.00, -1.22 (3.46)	0.85(16)	.20	0.21	

[a] Δ ITT: Intention-to-treat; PP: per-protocol

[b] Δ Comparison Wilcoxon rank-sum test

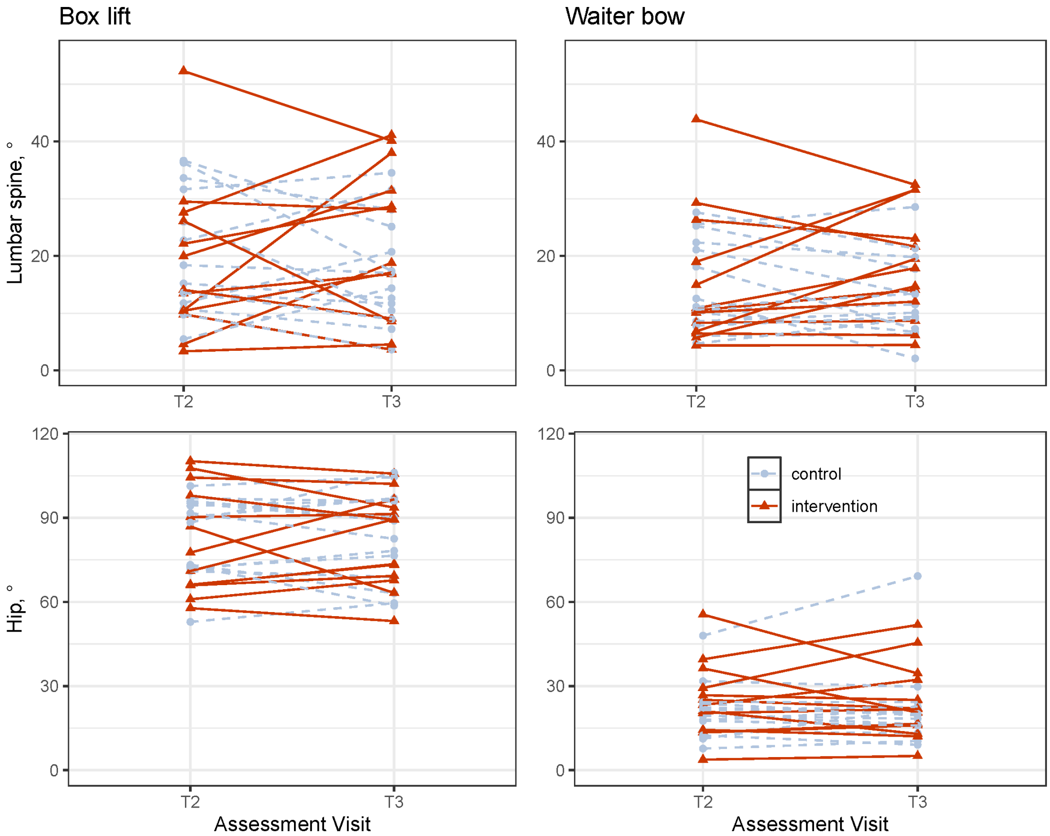

Figure 2.5: Lumbar spine and hip movement in degree during the Box Lift and Waiter Bow task at T2 and T3. Data as included in the intention-to-treat analysis (control: n = 14, intervention n = 13).

2.4.3.3 *Participant reported outcomes*

Neither in the ITT nor the PP analysis the groups significantly differed in the change of scores in participant reported outcomes were found (Table 2.6, Figure 2.6). Results on Psychological, Social and Environmental QOL are reported in Table 2.7, there were no significant effects.

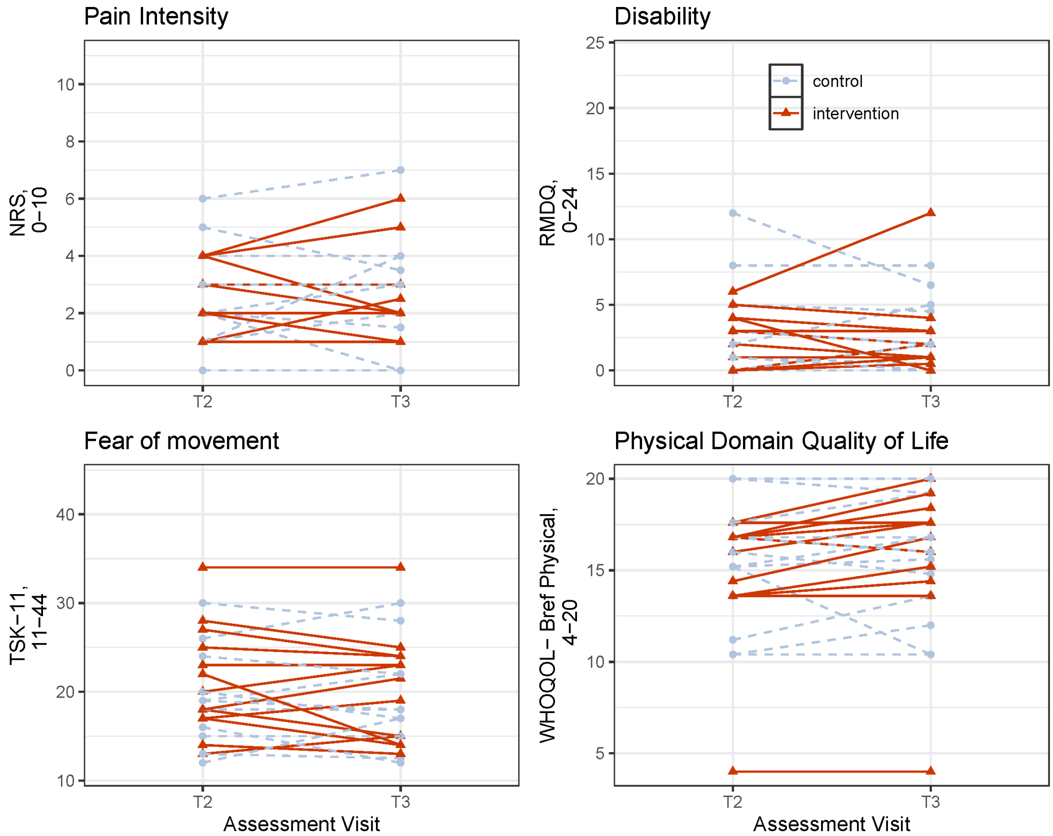

Figure 2.6: Scores of participant reported outcomes for the assessment visits T2 and T3. Data as included in the intention-to-treat analysis (control: n = 14, intervention n = 13) is displayed. NRS: Numeric Rating Scale; RMDQ Roland Morris Disability Questionnaire; TSK-11: Tampa Scale of Kinesiophobia -11 item version; WHOQOL-Bref Physical: Physical domain World Health Organization Quality Of Life Questionnaire – short version.

Table 2.7: Group comparisons of change from T2 to T3 of outcomes not reported in the main text.

Analysis[a]	Control	Intervention	Comparison		
	median, mean (SD)	median, mean (SD)	t(df)/W	P	r
Δ Mean medio-lateral Displacement					
ITT	-0.22, -0.36 (0.84)	-0.15, -0.36 (0.58)	89	.55[b]	0.02
PP	-0.18, -0.37 (1.05)	-0.29, -0.47 (0.61)	0.27(16)	.40	0.07
Δ Mean Global Displacement					

ITT	-0.14, -0.56 (1.12)	-0.18, -0.46 (0.80)	83	.66[b]	0.07
PP	-0.13, -0.68 (1.39)	-0.18, -0.39 (0.73)	39	.57[b]	0.03
Δ Mean anterior-posterior Velocity					
ITT	-0.21, -0.49 (1.26)	-0.41, -0.83 (1.29)	0.70(25)	.25	0.14
PP	-0.66, -0.76 (1.53)	-0.22, -0.87 (1.17)	0.18(16)	.43	0.05
Δ Mean medio-lateral Velocity					
ITT	-0.19, -0.33 (0.66)	-0.17, -0.23 (0.97)	-0.31(25)	.62.	0.06
PP	-0.26, -0.38 (0.73)	-0.17, -0.26 (0.52)	-0.41(16)	.66	0.10
Δ Mean Global Velocity					
ITT	-0.48, -0.65 (1.50)	-0.29, -0.92 (1.73)	0.44(25)	.33	0.09
PP	-0.78, -0.93 (1.81)	-0.23, -0.98 (1.35)	0.06(16)	.47	0.02
Δ Quality of Life- Psychological Subscale					
ITT	0.00, -0.19 (2.65)	0.00, -2.56 (1.26)	101.5	.71[b]	0.10
PP	1.33, -0.15 (3.36)	0.00, -0.44 (1.33)	50	.81[b]	0.20
Δ Quality of Life- Social Subscale					
ITT	0.00, 0.62 (1.35)	0.00, -0.15 (1.81)	114.5	.89[b]	0.23
PP	0.00, 0.89 (1.63)	0.00, 0.30 (1.86)	0.72(16)	.76	0.18
Δ Quality of Life- Environment Subscale					
ITT	0.00, 0.45 (1.32)	0.00, 0.44 (1.58)	94	.57	0.03
PP	0.00, 0.67 (1.60)	0.00, 0.22 (1.60)	50	.82[b]	0.20

[a] Δ ITT: Intention-to-treat; PP: per-protocol

[b] Δ Comparison Wilcoxon rank-sum test

2.4.4 *Exploratory comparisons across all assessment visits*

Exploratory analyses were conducted across all 4 assessment visits among a subset of participants, who remained in the study until T4 (n=20).

2.4.4.1 *Postural balance*

For Mean AP and global velocity no transformation was necessary. AP displacement, global displacement and ML velocity did not show significant effects of group, assessment visit or their interaction (Table 2.8), although the effect of assessment visit tended towards significance for ML and global displacement. For AP velocity and global velocity there was each a significant main effect of assessment visit, but none of the post hoc comparisons for the individual assessment visits showed significant differences. Descriptively displacement and velocity parameters increased between T1 and T2 and decreased from T2 to T3. This is surprising as we did not expect to see fluctuations in balance across time for the entire group of participants.

2.4.4.2 *Movement tasks*

There was no significant effect for group, assessment visit and the interaction for Lumbar Spine or Hip during the Waiter Bow and the Box Lift task (Table 2.8).

2.4.4.3 *Participant reported outcomes*

For the pain intensity NRS and Fear of Movement no significant effects for group, assessment visit or their interaction were present (Table 2.8). For the RMDQ scores, Friedman tests did not show significant differences across visits in the control group (χ^2_3 =4.1; P=.25) or the intervention group (χ^2_3 =6.0; P=.11). Bonferroni corrected Wilcoxon rank sum tests showed no difference of the groups at any assessment visit. However, for Physical QOL there was a significant main effect of assessment visit. Post hoc comparisons between assessment visits across both groups revealed that T3 scores were significantly higher than scores at T2 (t_{19}=-3.71; P=.009).

2.4.5 *Additional comparisons including all assessment visits.*

QOL Psychological Effect
To meet the requirements of a two-way mixed ANOVA Psychological Quality of life scores were transformed as log((x/4)+1). There was no statistically significant effect of Group: $F_{1, 18}$=0.01; P=.93; $\eta^2 G$ =0.00, Assessment Visit: $F_{3,54}$=0.87; P=.46; $\eta^2 G$ =0.00, and their interaction: $F_{3,54}$=2.60; P=.06; $\eta^2 G$ =0.01.

Social Quality of Life
No transformation was found for Social Quality of Life scores to fulfil the requirements of parametric analysis. There was no effect of Assessment visit on social

quality of life in the control group χ^2_3 =2.69; P=.44 and neither in the intervention group χ^2_3 =5.76; P=.12 using Friedmann tests. None of the Bonferroni corrected Wilcoxon rank sum tests at each assessment visit showed statistically significant differences between the groups.

Environmental Quality of Life

Environmental Quality of Life could not be transformed to satisfy the assumptions of a two-way mixed ANOVA. Friedmann tests showed no effect of Assessment visit on social quality of life in the control group χ^2_3 =2.12; P=.55 and neither in the intervention group χ^2_3 =0.76; P=.86. None of the Bonferroni corrected Wilcoxon rank sum tests comparing groups at each assessment visit was statistically significant.

Table 2.8: Effects of Group and Assessment Visit on Postural Balance parameters within two-way mixed ANOVA.

Group			Assessment Visit			Group* Assessment Visit		
F(df)	P	η^2G^n	F(df)	P	η^2G	F(df)	P	η^2G
Mean anterior-posterior Displacement								
0.25(1, 18)	.63	0.01	1.51(3, 54)	.22	0.02	1.21(3, 54)	.32	0.01
Mean medio-lateral Displacement								
1.21(1, 18)	.29	0.05	2.52(3, 54)	.07	0.03	0.10(3, 54)	.96	0.00
Mean Global Displacement								
0.71(1, 18)	.41	0.03	2.59(3, 54)	.06	0.02	0.51(3, 54)	.68	0.01
Mean anterior-posterior Velocity								
1.60(1, 18)	.22	0.07	3.51(3, 54)	.02	0.03	0.28(3, 54)	.84	0.00
Mean medio-lateral Velocity								
0.03(1, 18)	.87	0.00	2.07(3, 54)	.12	0.01	0.21(3, 54)	.89	0.00
Mean Global Velocity								
0.50(1, 18)	.49	0.02	3.61(3, 54)	.02	0.03	0.12(3, 54)	.95	0.00
Box Lift Lumbar Spine								
0.00(1, 18)	.99	0.00	1.32(3, 54)	.28	0.02	1.56(3, 54)	.21	0.03
Box Lift Hip								
0.06(1, 18)	.81	0.00	0.27(3, 54)	.85	0.00	0.91(3, 54)	.44	0.01
Waiter Bow Lumbar Spine								

0.54(1, 18)	.47	0.02	0.22(1.89,34.01)	.79[b]	0.00	0.82(1.89,34.01)	.44[b]	0.02
Waiter Bow Hip								
0.15(1, 18)	.71	0.01	1.40(3, 54)	.24	0.02	0.42(3, 54)	.74	0.01
Pain Intensity Numeric Rating Scale								
0.94(1, 18)	.35	0.02	1.34(3, 54)	.27	0.04	0.76(3, 54)	.52	0.02
Quality of Life- Physical Subscale								
0.26(1, 18)	.62	0.01	5.55(1.78, 31.98)	.01[b]	0.04	1.08(1.78, 31.98)	.34[b]	0.01
Tampa Scale of Kinesiophobia- 11 Item version								
0.22(1, 18)	.64	0.01	1.05(3, 54)	.38	0.01	0.14(3, 54)	.93	0.00

[a] Δ Generalized eta squared.

[b] Δ Greenhouse Geisser corrected.

2.4.6 *Adherence*

Participants in the intervention group were instructed to complete a fixed set of 90 exercises between the assessments T2 and T3. Of these exercises, a Median of 61% exercises (55/90; Min=2%; Max=99%) were completed. As not all exercises were performed with the specified duration and frequency; and some participants did exercises that were provided from the device, but were not intended as part of the program, effective time spent exercising differed from the completion of the program. In this period with a predefined schedule (T2-T3), participants exercised a Median of 77% (139/180, Min=3%; Max=202%) of the targeted exercising duration of 180 minutes. The exercising time of 4 participants exceeded 180 minutes. During the intervention period with a schedule, 7 participants performed a Median of 9 exercises (Min=1; Max=41), equivalent to 17 minutes (Min=2; Max=109) that were not part of the program. In the intervention period without a schedule, of 11 participants who had remained in the study, 4 participants performed a median of 27 exercises (Min=1; Max=29), equivalent to 82 minutes (Min=2; Max=101). An overview on the adherence data is provided in Figure 2.7.

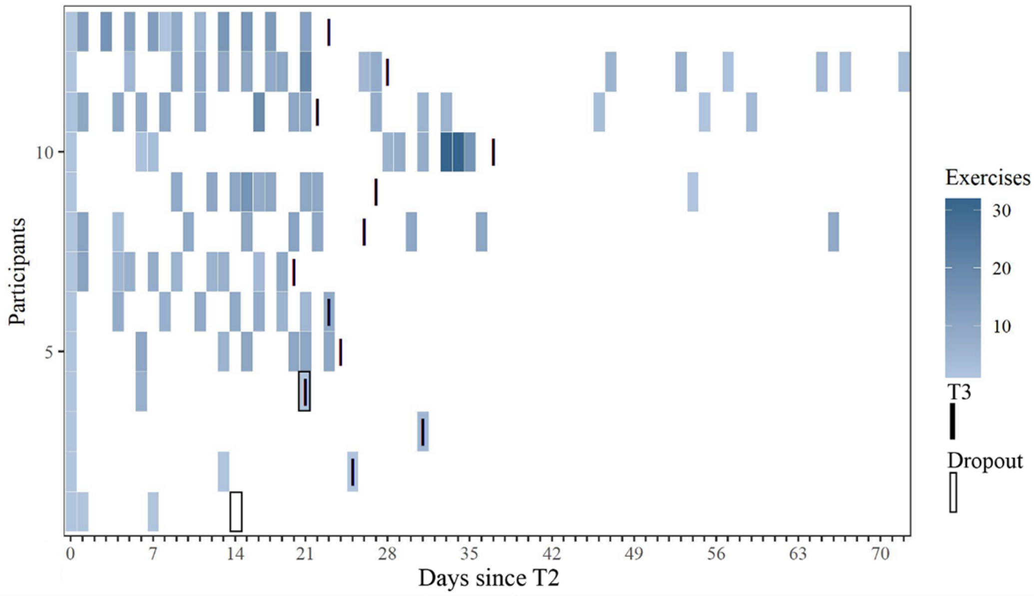

Figure 2.7: Exercises completed during the study per participant. Darker color indicates a larger number of exercises performed on a given day. All exercises, including exercises that have not been intended as a part of the exercise program are displayed. Black bars show assessment visit T3, black boxes show dropouts.

2.4.7 *Unintended effects*

There were no unintended effects that were related to the intervention. Although reasons for not adhering to the protocol were not assessed systematically and participants had been encouraged to contact the investigators with any difficulties, some participants in the intervention group reported problems with handling the devices. This included difficulties such as finding the right icon on the tablet and difficulties with the calibration of the IMUs and program failures of the tablet. These issues likely contributed to the low adherence of some participants.

2.5 DISCUSSION

2.5.1 *Principal findings*

Self-directed home exercising with feedback on trunk movements for a period of approximately three weeks did not enhance postural balance during quiet standing in study participants with LBP or significantly affected any other of the investigated outcomes. Comparisons of the groups with respect to the movement tasks indicated a tendency towards slightly increased motion of the lumbar spine during both tasks in the intervention group, combined with a small reduction in the control group, which contradicted our predictions. Adherence to the scheduled exercising program was low. After the participants were no longer provided with a schedule to complete, only some participants kept using the training device repeatedly without specific instructions. Despite not showing intervention effects in this trial, it cannot be excluded that these interventions may still be beneficial when integrated into a therapy setting with patients. Further, for other exercising interventions it has been demonstrated that exercising could have a more pronounced effects in patients than in other study participants with LBP (Hayden et al., 2005). A review showed that the results were positive for exercising with digital systems for LBP, when these exercises were delivered together with another intervention, but otherwise not (Matheve et al., 2017).

2.5.2 *Comparison to prior work*

2.5.2.1 *Postural balance*

In this study investigating an exercise intervention using mobile sensors under self-directed home conditions in people with moderate LBP, we found no improvement of postural balance during quiet standing. To our knowledge no other studies using feedback on trunk movements and similar assessments of postural balance have been conducted with participants with LBP. In a study where exergaming with the Nintendo Wii was included into the treatment, participants were not able to maintain single-legged stance for longer than before the intervention (Park et al., 2013). In contrast, in a study with elderly participants with diverse chronic musculoskeletal complaints, an exergame that mainly focused on translations of the body weight, several postural balance parameters improved, but not relative to participants who had performed similar exercises without gamification (Ditchburn et al., 2020). A meta-analysis on studies with elderly participants without complaints suggests, that exergames affect different measures of postural balance positively, but an enhancement of postural balance assessed under stable, unperturbed conditions could not be confirmed either (Fang et al., 2020). Consistent with these observations, differences observable at the level of the trunk may not necessarily translate to changes in COP based assessments during quiet standing (Schelldorfer et al., 2015). Postural balance regulation is the product of the complex interaction of different structures and systems, with the capacity to adapt to changing conditions (Shumway-Cook and Woollacott, 2017). Other assessment conditions e.g. assessments of trunk balance during sitting may provide a clearer picture of trunk control (Dieën et al., 2019) and could reveal more subtle changes. Unexpectedly, we observed changes in some postural balance parameters across assessment visits, but statistically significant differences between individual visits were not found. The descriptive pattern did not indicate a continuous trend that could have been interpreted as learning or other effects of repetition.

2.5.2.2 *Movement Tasks*

In this study, the average amount of lumbar spine movement observed was comparable to the values reported earlier by other researchers (Matheve et al., 2018c). However, contrary to our expectations, descriptively the participants in the intervention group showed small increases in movement in the lumbar region during the movement tasks, compared to the control group, which showed comparable reductions. This was the case despite the instructions to not bend or extend the lumbar spine during the assessment. Nevertheless, if only the increase in lumbar spine motion in the intervention group independently of the decrease in the control group is considered, this increase was only during the Box Lift task in the PP analysis (6.03°) slightly larger than the minimally detectable change value of 5.3° described in the study, our assessments were adapted from (Matheve et al., 2018c). Other investigators found an expansion in ROM after a similar intervention, but did not clearly state whether there was a difference in comparison to the group without the exercises (Magnusson et al., 2008). No impact on an intervention on ROM was found in another study (Kent et al., 2015). A recent meta-analysis challenged the assumption, that people with LBP tend to bend their spine more in lift tasks (Saraceni et al., 2020) and restrictions in ROM in the lumbar region of people with LBP have already been described (Laird et al., 2014). Furthermore, it was found that during a Box Lift task, participants with chronic LBP moved less in the lumbar region than participants without LBP (Matheve et al., 2019). Hence, an increase in movement in the lumbar spine would not necessarily constitute an undesirable outcome. Future studies should clarify the role of lumbar spine posture during lifting and the influence of exercising interventions on lifting behavior.

2.5.2.3 *Participant reported outcomes*

There were no statistically significant differences between the change scores of groups in participant reported outcomes. In contrast, some other studies investigating similar interventions found positive effects on pain assessments (Magnusson et al., 2008; Kent et al., 2015). Nevertheless, it should be taken into account, that pain numeric rating scales could be error prone to some degree (Chiarotto et al., 2019) and the power in this study may have been insufficient to detect an effect. A reduction in pain intensity across both groups was observed within the first 3 weeks of the study, where no intervention was provided. This effect could possibly be caused participants initiating study participation during periods in which their pain was perceived as slightly worse than usual. The amount of pain appeared to be roughly comparable to the value of approximately 2.5 obtained from visual analog scales, which had been reported in a review which revealed postural balance differences between people with and without LBP (Ruhe et al., 2011). As we have observed, a small study found that exercises with postural feedback in addition to standard care was not superior in reducing disability than usual treatment alone (Hügli et al., 2015). This is in contrast with the results of a different study, which indicated that disability could be improved (Kent et al., 2015). However, in that specific study the feedback from the wearable device was not only provided during exercises but also during everyday activities (Kent et al., 2015). In our study the RMDQ mean scores were generally low, which may have limited the range of possible improvement. We did not find an intervention effect on physical quality of life. Contrary to this result, in another study an intervention effect on the physical subscale of the QOL measure Short Form-36 was observed (Magnusson et al., 2008). We did not find an effect of the intervention on fear of movement, and neither an intervention effect was found in another study (Kent et al., 2015).

.

2.5.2.4 *Adherence*

A particular strength of the presented work is the combination of an investigation of the exercising program at home in a period with a set training schedule, and in a second interval, where participants could exercise as they wished. Comparison to studies on related interventions in home based settings which are considered similar are difficult, as in one study a combined value including other exercises was investigated (Hügli et al., 2015) and in another study self-report methods had failed (Matheve et al., 2018b). Furthermore, in a study that investigated exercising with the Nintendo Wii, a completion of 71% of the advised time was achieved (Zadro et al., 2019), which is comparable to the median of 77% we obtained. Nevertheless, the schedule provided was much more demanding and additional measures were used to improve adherence in the other study (Zadro et al., 2019). Results on adherence considering time spent exercising was more favorable than the number of exercises performed as requested by the investigators. Some participants exercised even more than required but did not follow the instructions precisely. In some cases, participants may have forgotten to reset the play time from the default 4 to 2 minutes, or the game may have motivated the participants to explore additional contents and may have provided stronger guidance than the instructions from the investigators. The 6-week period with flexible exercising opportunity resembled more closely conditions under which participants would be using such tools without the connection to a therapeutic setting. Only few participants kept exercising after T3. These results may imply that such interventions only get adopted by a small number of people or might rather be integrated within supervised programs on site. Within the setup of this study, it could not be determined, whether the provided schedule, or the participants' commitment to comply with the study protocol resulted in higher amounts of exercises between T2 and T3. Future studies should investigate if and how automated scheduling options can help to improve adherence and how they should be integrated. While the VALEDO app offers the option to generate an exercising plan, such functions could be placed more prominently.

2.5.3 *Limitations*

The low number of participants who could be recruited is an important limitation of this study. Although the individual components of the study protocol may not have been too time consuming, the overall effort associated with study participation, including diary methods and activity tracking not included in this manuscript, may have been a cause for low recruitment and retention rates. These assessments were included to answer additional research questions beyond the scope of a single manuscript, but contributed to the effort for study participants. In line with this presumption, reasons given for withdrawal were frequently related to time investment or perceived benefit and effort. This might also have contributed to the low adherence to the intervention. Time intervals between assessments were slightly stretched, due to frequent requests from participants to reschedule appointments, as the study participation was not part of an official treatment program and therefore often had to take place often outside of the working hours of the participants. The assessment of the movement tasks was preceded and followed by the participants shifting their weight to the sides and back, to time synchronize the data from the IMUs with data collected simultaneously from the force platform. Although supporting analyses of change between T2 and T3, where data from trials that appeared to be performed from an unstable starting position were removed appeared similar, this setup could have influenced the results. The study participants could not be blinded and with most assessments conducted in the field, it could not be ruled out that the participants completed all exercises themselves. In one case with a particularly high number of exercises it was suspected that other people may have completed some of those exercises. Further, although we consider the availability of the questionnaires in different language versions as a strength, this setup may have caused inconsistencies between the questionnaires different participants received.

2.5.4 *Conclusion*

The results obtained in this study indicate that exercising with feedback on trunk movements may not influence postural balance during quiet standing in people with only moderate LBP intensity and disability. No significant intervention effects on lumbar spine and hip movement, pain intensity, disability, QOL domains and fear of movement were observed. There was a tendency towards improvements in pain intensity among participants who adhered to the intervention. These results have to be seen within the context of a small sample size and the low adherence to the intervention. More work in this field is required, for example to establish the effect of interventions using feedback on trunk movements in people more severely affected by LBP and to clarify more proximal effects on trunk stiffness and proprioception. Since the amount of exercising dropped substantially in the intervention period without a schedule, future studies should investigate the impact of different scheduling options.

3 FEAR OF MOVEMENT AND POSTURAL BALANCE

In the previous chapter we have assessed, whether a sensor-based intervention, which required the users to move their torso on different planes, can change different outcomes. Among those, an assessment of fear of movement was not responsive to the intervention. The literature has proposed that the amount of fear can differ for individual movements (Leeuw et al., 2007; Pincus et al., 2010) and some research integrating assessments of fear for defined tasks or movements has been conducted (Karayannis et al., 2013; Knechtle et al., 2021; Matheve et al., 2019; Thomas et al., 2016). In this chapter we examine, whether fear in general, and fear of movements along different movement planes impact postural balance.

This chapter is based on:
Meinke, Anita, Maschio, Cinzia, Meier, Michael, Swanenburg, Jaap, Karlen, Walter. The Association of Fear of Movement and Postural Balance in People with Low Back Pain. *in preparation for submission*

My contributions to this chapter are the conceptualization of the research question and practical integration of the project into the existing RCT. I planned and performed the data analysis and wrote the manuscript. I did all of this in consultation with my coauthors, who have edited and commented on the manuscript. Cincia Maschio wrote her master thesis within this project, using a subset of the data. This work centers around a secondary analysis of data form the RCT presented in chapter 2, therefore the acknowledgement section of chapter 2 applies to this work as well. In addition to contributions from the coauthors, Laura Tüshaus reviewed and suggested improvements to the specific fear questions. Statistical advice was obtained from the Seminar for Statistics at ETH Zurich.

3.1 abstract

Background: Pain related fears are thought to be detrimental inhibitors for the recovery of people with low back pain (LBP). However, the relationship between fears and movement characteristics such as balance is not yet adequately understood. Recent findings suggest that fears need to be assessed specific to a movement task to better understand their relation with movement characteristics. Therefore, the fear to move the trunk in a certain direction could be distinctly related to the amount of postural sway in different directions. Our aim was to investigate whether and how fear in general and fear associated with movement on a certain movement plane relate to postural sway.

Methods: Data was collected from people with LBP from two assessments that were approximately three weeks apart. Postural sway was measured with a force-platform during quiet standing. Fear of movement was assessed with an abbreviated version of the Tampa Scale of Kinesiophobia (TSK-11) and custom items referring to fear from trunk movements on the sagittal and the frontal plane.

Results: Based on 59 observations from 32 participants, no relation of the TSK-11 with direction unspecific mean sway displacement and the mean sway velocity was found. Forty-one observations from 25 participants available for direction specific analyses, showed a positive relation of the TSK-11 with velocity of the frontal plane (P=.008). Fear of movements on the frontal plane was positively related to displacement on the sagittal and frontal plane and velocity on the frontal plane (P=.04; P=.004; P=.002). Fear of movements on the sagittal plane was not associated with any direction specific measure of sway. A measure of relative directional fear showed that relatively stronger fear in the frontal plane was associated with larger sway in comparison to relatively stronger fear for the sagittal plane, tending towards lower sway. This pattern was observed for displacement on the sagittal and frontal plane and for velocity on the frontal plane (P=.002; P=.005; P=.008).

Discussion: Fear of movement in the frontal plane may be more relevant to postural balance than fear of movement in the sagittal plane. The underlying mechanisms which could lead to this effect should be clarified. The direction which is feared more might play a role for postural balance, but further analyses are required.

Conclusion: For the first time the directional relationship of fear of movement and postural sway was studied by investigating the postural sway with a sensor platform. Fear of movement on the frontal plane may be more relevant to postural sway than fear of movement on the sagittal plane.

3.2 BACKGROUND

3.2.1 *Importance of fear of movement for people with LBP*

According to the global burden of disease study, the disability generated by low back pain (LBP) is considered to be larger than for any other complaint (Wu et al., 2020). A relation between disability assessments and fear in people with LBP (Carvalho et al., 2017; Costa et al., 2011; Nordstoga et al., 2019) and other similar pain conditions (Luque-Suarez et al., 2019) is often observed. Further, a review showed that stronger fears during subacute LBP may promote difficulties to get back into office (Wertli et al., 2014).

That fears bring about adverse outcomes in people with LBP has been a suspected already for a long time (Vlaeyen and Crombez, 1999). The basic premise of this line of work is that people who respond to pain with fear and withdrawal from activities regarded as potentially harmful, could lose the benefits from physical activity and movement on their back health and thus might consolidate their pain even further (Vlaeyen and Crombez, 1999). However, not all data confirm this model (Costa et al., 2011; Pincus et al., 2010) and a reduction in physical activity with increased fear was not observed in a study of Carvalho et al. (2017). A wealth of research indicates that LBP is linked to movement behavior (Dieën et al., 2019). While these altered movements may serve to avoid physical stress in some areas, they could possibly cause additional stress in other areas that are not the focus of the safety behavior, and may jeopardize back health (Dieën et al., 2019). Van Dieën et al. (2019) further remark that if these reactions are provoked by unjustified fears, they could be purely detrimental without any adaptive value.

3.2.2 *Association of fear with movement characteristics*

Lately a meta-analysis confirmed that people with LBP and greater fear may restrain their movement of the spine (Christe et al., 2021). In line with this observation, Karayannis et al. (2013) found a higher rigidity in reaction to perturbations of the torso and flexion movements on the sagittal plane seem to be commenced more slowly when fear of movement is greater (Nordstoga et al., 2019; Osumi et al., 2019). Further, people with greater fear and LBP may be more imprecise in tracing a requested movement trajectory by flexing and extending their torso (Alsubaie et al., 2021). Assessments of postural balance are commonly used in studies investigating LBP. *"Balance is a generic term describing the dynamics of body posture to prevent falling"* (Winter, 1995, p.194), and the operation of the sensorimotor system regulating balance can be observed by describing the pathway of the vertical ground reaction force, the COP (Winter, 1995). Although this is technically not accurate (Winter, 1995), for simplicity we will discuss COP based parameters as assessments of body sway.

Several reviews have summarized research results on sway in people with LBP (Berenshteyn et al., 2019; Mazaheri et al., 2013; Ruhe et al., 2011). Two of the reviews highlighted the enlarged sway parameters found in people with LBP (Berenshteyn et al., 2019; Ruhe et al., 2011), while another review emphasized that this was not the case for a subset of studies (Mazaheri et al., 2013). Further investigations of the impact of fear on sway assessments in general was suggested (Berenshteyn et al., 2019; Mazaheri et al., 2013) and additionally that fear may cause some of the observed heterogeneity by counteracting other mechanisms associated with pain (Mazaheri et al., 2013). As a mechanism behind this effect a rising muscle tension due to fear was proposed (Kiers et al., 2015). Mazaheri et al. (2014) evaluated the assumptions of counteracting mechanisms in another study and inferred from their findings that fear did not have much impact on sway. However, the association of fear and sway was not directly analyzed (Mazaheri et al., 2014). Instead, the inference was made by comparison of a group of people who had just overcome LBP, as fear was not diminished in this group yet, to people with ongoing and without LBP (Mazaheri et al., 2014). In addition, other studies have reported data on the influence of fear on postural sway or other balance measures in people with

LBP (Hlaing et al., 2020; Jacobs et al., 2016; Kahraman et al., 2018; Shanbehzadeh et al., 2018; Sung et al., 2015; Zhang et al., 2020). Shanbehzadeh et al. (2018) found that participants with greater fear swayed less. In another study fear was negatively associated with some limits of stability measures and in men alone there was a positive association with a measure combining sway across different manipulations of sensory input while standing quietly (Kahraman et al., 2018). No relation between sway and fear was found when the participants stood on one leg (Kahraman et al., 2018). Neither Hlaing et al. (2020) found a relation of fear with the time participants could stand on one leg on firm ground, but observed that times for standing on one leg on compliant ground were reduced in participants with higher fear. However, in a cohort of people who had not become chronic yet and who displayed reduced motor control capabilities in movement assessments, balance during sitting on a platform that was only supported in the center was not found to correlate with fear (Sung et al., 2015). In one study investigating how much the body shifted when reacting to tilts of the supporting ground, indicated a relation with fear (Jacobs et al., 2016). In addition to the results concerning fear, catastrophic thoughts in people with chronic LBP appear to be linked to sway, although the direction of this effect was reported inconsistently (Zhang et al., 2020). Thus, while there is some first evidence of a relationship of fears and postural balance, the relationship between balance and fear has not yet fully been clarified.

3.2.3 *Movement specific fear*

It has been argued that commonly used comprehensive assessments of fear do not capture the selectivity of fears of distinct movements (Leeuw et al., 2007) and thus make it harder to detect associations of fear with movement characteristics (Matheve et al., 2019; Pincus et al., 2010). Indeed, in their study Matheve et al. (2019) only identified a negative association with movement in the lumbar region during lifting with a measure directly quantifying fear of lifting, but not with common assessment tools. Further research confirmed analogous findings in people without pain (Knechtle et al., 2021) and by referring to such results, other researchers emphasized that more targeted assessments should be used (Christe et al., 2021). In contrast, Karayannis et al. (2013) described that common assessments of fear, but not an item designed to capture fear of the task was linked to rigidity of the torso. That fear can be associated with certain movements in particular might also be relevant for assessing the influence of fear on postural balance. As people could differ in the movements that elicit pain and which are considered to be harmful for their back, direction specific fears might result for example in a restriction of sway in the movement plane corresponding to the fear. We therefore assumed that fears from spinal flexion in different directions might relate differently to postural sway on different planes.

3.2.4 *Research goals*

To gain further insights into the relationship between fear of movement and postural sway we conducted a retrospective analysis of COP data obtained from people with LBP. Our aim was to investigate whether postural sway, described by mean displacement and velocity, is affected by fear of movement in general, and whether fear of movements on different planes affect sway for the corresponding movement directions.

3.3 METHODS

3.3.1 *Study design and participants*

We describe secondary analyses of data from a RCT that investigated the effects an exergame for people with LBP (Meinke et al., 2021). Data of two baseline assessments taken approximately 3 weeks apart was used. Participants had not been randomized or received any intervention at the time the data was obtained. The participants were recruited by leaflets, online advertisement, and personal interaction. Participants were included if they had back pain in the lower region, were above age 18, not in any therapies for LBP for the past half year before study participation and gave their informed consent. Participants were excluded from the study due to radicular symptoms or other specific causes of LBP, pain perceived as too strong to complete the investigated exergame or vision too low to use the exergame, pharmacological treatment that negatively influences balance, allergies to the band used to stick the sensors to the skin, pregnant women, or language barriers. Ethics approval was received from the Cantonal Ethics Committee Zurich, Switzerland (BASEC-2018-02132).

3.3.2 *Procedures*

Data on fear of movement, postural sway and pain intensity was collected at both assessments. A numeric rating scale (0-10) was used to query pain intensity in the last 7 days (Chiarotto et al., 2018). Weight and height were assessed at the first measurement occasion. Fear of movement was assessed among other variables at site using an online form through RedCap (Harris et al., 2009). All participants used the same screen to take the survey before the other assessments were carried out. Questions were either presented in English or German.

3.3.3 *Fear of movement*

For a global score of fear of movement, the abbreviated version of the Tampa scale for Kinesiophobia (TSK-11) was used (Rusu et al., 2014; Woby et al., 2005). The English assessment showed a good quality, which was comparable to the full scale in patients with chronic LBP (Woby et al., 2005). The German TSK-11 is valid and sufficiently internally consistent (Rusu et al., 2014). Direction specific items were included later into the project, therefore this data stems from less participants. For an assessment of fear for different movement planes, a custom question type was used. Earlier studies which had integrated fear assessments more directly related to the movements under investigation mentioned above, used additional items in the identical format (Karayannis et al., 2013), or items already available (Knechtle et al., 2021; Matheve et al., 2019) within the Photograph Series of Daily Activities-Short Electronic Version (PHODA-SEV) (Leeuw et al., 2007). Although the PHODA-SEV was designed to comprise of movement examples for different planes, the resulting scale mean does not distinguish these planes. Similar to the style of the PHODA-SEV, we asked participants to rate their fear of movements of the torso in different directions (Figure 3.1). As the PHODA-SEV includes photographs to visualize the corresponding movement, we added symbols to clarify the movement referenced in the questions. The fear assessment for the sagittal plane was defined as the mean of the items referring to flexion and extension. A measure for relative directional fear was calculated by subtracting the fear rating for the frontal plane from the fear rating of the sagittal plane. Negative values describe higher fear ratings for the frontal plane movement, while positive values describe relatively stronger fears in the sagittal direction. Values close to zero describe no distinction between frontal and sagittal plane movements.

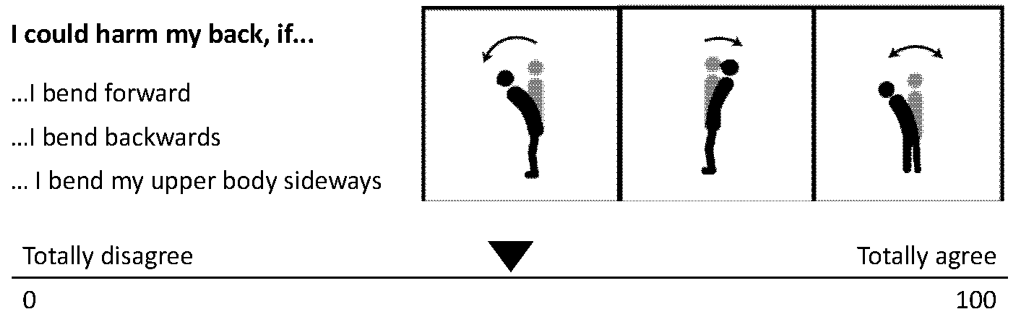

Figure 3.1: Question format used for specific Fear of Movement questions.

3.3.4 *Assessment of postural sway*

The assessment was implemented according to the advice from Ruhe et al. (2010). The COP assessments were derived from a pressure plate (AMTI, Accusway Plus, Watertown, MA, USA). Participants maintained upright stance as quietly as they could and kept their hands loosely hanging. The participants were told to close their eyes during the assessments and wore a shaded ski mask. The exact stance of the participants was outlined on an underlayment to replicate the original stance in subsequent recordings. The assessment was performed for 120 seconds in 4 consecutive trials with short breaks in between. Each trial the central 110 seconds were analyzed. After filtering the recordings with a low-pass fourth order Butterworth filter (10 Hz cut-off frequency) mean displacement from the center and velocity and their direction specific versions were calculated (Prieto et al., 1996) and averaged across the repetitions collected at one assessment occasion.

3.3.5 *Statistical methods*

R (R Core Team, 2021) version 4.04 and lme4 (Bates et al., 2015) were mainly used for the statistical tests. We used mixed effects linear models to test our research questions. Continuous predictors including pain scores and fear assessments were standardized across the entire sample before inclusion into the models. Normal distribution of the residuals and random intercepts were assessed using normal-qq plots and the presence of heteroscedasticity was reviewed by plotting the predicted values against the residuals. The residuals were further plotted against each predictor variable individually. These analyses were performed for the untransformed, log(x+1), square root transformed and reciprocally transformed data. Based on the residual analysis the models with log transformed outcomes were chosen. For each postural sway outcome, we estimated a first model to assess the effect of potential confounding factors (assessment occasion, sex, age, height, weight and pain). Based on the results of this analysis of confounding factors, we included the variables assessment and age as fixed effects in the baseline models for all sway outcomes. Effects of the fear variables were tested by adding each individual variable of interest to the baseline model and comparing the resulting model against the baseline model only. All models included the participants as random effect. The influence of individual participants on the models was assessed using cook's distance calculated with Influence.ME (Nieuwenhuis et al., 2012). Each participant classified as influential was removed from the models separately and comparisons were reevaluated to see if individual participants could have affected the statistical significance of the results. Reliability of fear assessments was estimated using ICC model (2,1), relying on the ANOVA results as implemented in the package psych (Revelle, 2021). Reliability estimates were based on data from participants who completed the questionnaires at both assessment occasions.

3.4 RESULTS

3.4.1 *Participant characteristics*

Characteristics of the participants involved, fear of movement and balance estimates are presented in Table 3.1. Intra-class-correlations for specific fear variables are presented in Table 3.2. As the specific fear questions had been added later to the investigation, this data stems from 25 unique participants, of which 16 contributed data both for visit 1 and 2. Relative directional fear was calculated by subtraction of fear on the frontal plane from fear on the sagittal plane. Figure 3.2 shows that participants who reported higher fear for the sagittal plane relative to the frontal plane, had in general lower values of fear.

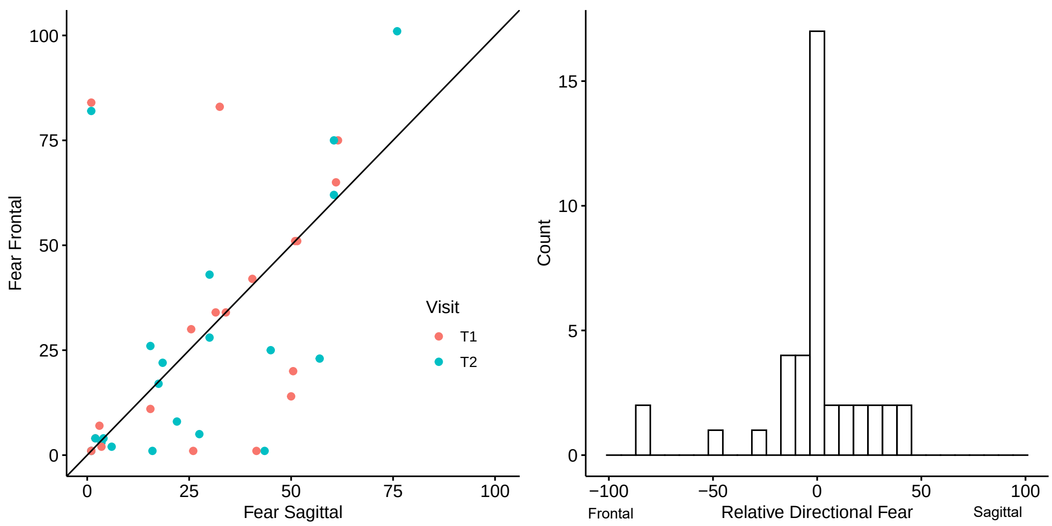

Figure 3.2: Relative directional fear is calculated by substracting fear frontal from fear sagittal. Negative values for relative directional fear show higher fear of frontal plane movements and positive values show higher fear of sagittal plane movements.

3.4.2 *Effect of FOM on postural sway*

The assessment of confounding factors and resulting baseline models resulted in assessment occasion, age and weight to be included in the baseline models for all outcomes (Table 3.3). General fear as measured by the TSK-11 was no associated with mean displacement and velocity in general (Table 3.4). However, for the directional sway measures, association was found with velocity of sway on the frontal plane. The fear assessment for the sagittal plane was not associated with any of the direction specific sway measures. The fear assessment for the frontal plane was associated with displacement and velocity in the frontal plane, but also with displacement on the sagittal plane. The predictor relative directional fear showed the same pattern of associations.

We tested whether removing individual participants that had been identified as influential by using cook's distance would have changed the results of the model comparisons. If these participants were removed the results could have become not significant in two cases for the effect of fear on the frontal plane on displacement in the sagittal plane. In addition, the effect of the TSK-11 on displacement in the frontal plane would have become statistically significant, if one case was removed.

The correlation coefficients in the untransformed direction specific data show that descriptively displacement and velocity both tended to be higher with higher fears (Figure 3.3 and 3.4). Relative directional fear described a weighting of the directions relative to each other, with the general response trend removed (e.g., generally high or low fear ratings for both planes). Negative values indicated relatively stronger fears towards frontal plane movements and while positive values described stronger fears in sagittal plane. Thus, the negative correlations observed in this study showed that relatively higher fear of frontal plane movements were associated with higher displacement in both directions.

Graphical inspection revealed that of the movements comprised in movement on the sagittal plane, flexion alone may have a positive association with different specific postural sway outcomes, but not extension. Therefore, although these were not pre-planned analyses, additional model comparisons for flexion and extension were conducted. Neither flexion nor extension on the sagittal plane independently had a statistically significant effect on any of the direction specific postural sway outcomes.

Table 3.1: Descriptive Statistics of participant characteristics, fear assessments and postural balance outcomes at both assessment occasions.

Variable	Assessment 1 M (SD) [a] /Mdn (IQR)[b]	Assessment 2 M (SD)/Mdn (IQR)
Participant characteristics		
N	32	27
Age	37.50 (24.75) [b]	35.00 (25.5) [b]
Height	171.26 (7.92)	172.05 (7.65)
Sex (male/female)	11/21	10/17
Language (English/German)	6/26	5/22
Pain Intensity	3.19 (1.47)	2.59 (1.34)
Fear assessments		
TSK-11	19.59 (4.41)	19.96 (5.62)
n direction specific fear variables	20	21
Fear flexion	23.00 (50) [b]	18.00 (26) [b]
Fear extension	31.50 (49.5)[b]	17.00 (49) [b]
Fear sagittal	32.00 (46.75) [b]	18.50 (39.5) [b]
Fear frontal	25.00 (47.5) [b]	17.00 (25) [b]
Relative directional fear	0.00 (6.25) [b]	0.00 (17.5) [b]
Postural Balance		
Displacement	4.82 (1.71) [b]	5.78 (1.99)
Displacement sagittal	4.04 (1.46) [b]	4.57 (1.49)
Displacement frontal	1.99 (1.18) [b]	2.61 (1.31)
Velocity	10.47 (2.96)	11.14 (2.72)
Velocity sagittal	8.84 (2.64)	9.48 (2.23)
Velocity frontal	3.54 (1.72) [b]	3.77 (2.31) [b]

[a] M (SD): Mean (standard deviation).

[b] Mdn (IQR): Median (inter quartile range)

Table 3.2: Reliability estimates for specific fear questions (n = 16).

Variable	ICC[a]
Fear flexion	0.75 (0.56 to 0.87)
Fear extension	0.57 (0.31 to 0.76)
Fear sagittal	0.68 (0.38 to 0.86)
Fear frontal	0.74 (0.47 to 0.89)
Relative directional fear	0.84 (0.66 to 0.93)

[a] Intraclass correlation coefficient. Estimate and (95% CI)

Table 3.3: Influence of confounding variables.

	Predictor		Outcomes			
	Displacement	Velocity	Displacement		Velocity	
			Sagittal	Frontal	Sagittal	Frontal
n comparison	32	32	25	25	25	25
Potential Confounders						
Assessment	0.07 (-0.00 to 0.13)	0.04 (-0.02 to 0.10)	0.03 (-0.07 to 0.11)	**0.16 (0.05 to 0.27)**	0.07 (-0.01 to 0.15)	0.06 (-0.02 to 0.14)
Sex	0.04 (-0.19 to 0.27)	-0.02 (-0.21 to 0.17)	0.07 (-0.13 to 0.26)	0.14 (-0.14 to 0.43)	0.02 (-0.19 to 0.22)	0.05 (-0.18 to 0.29)
Age	0.01 (-0.08 to 0.10)	**0.08 (0.01 to 0.16)**	-0.05 (-0.13 to 0.03)	0.09 (-0.03 to 0.21)	**0.09 (0.01 to 0.17)**	0.04 (-0.06 to 0.13)
Height	0.04 (-0.08 to 0.15)	0.03 (-0.07 to 0.12)	-0.07 (-0.18 to 0.03)	-0.02 (-0.17 to 0.13)	-0.02 (-0.12 to 0.09)	-0.03 (-0.15 to 0.09)
Weight	-0.05 (-0.14 to 0.04)	0.05 (-0.02 to 0.13)	0.04 (-0.05 to 0.13)	-0.01 (-0.14 to 0.12)	0.09 (-0.00 to 0.19)	0.08 (-0.02 to 0.19)
Pain Intensity	0.02 (-0.03 to 0.07)	0.01 (-0.03 to 0.06)	-0.00 (-0.06 to 0.05)	0.04 (-0.03 to 0.11)	0.01 (-0.05 to 0.06)	0.03 (-0.03 to 0.08)
Baseline model						
Assessment	0.06 (-0.01 to 0.12)	0.03 (-0.02 to 0.09)	0.03 (-0.06 to 0.11)	**0.13 (0.03 to 0.24)**	0.07 (-0.01 to 0.14)	0.04 (-0.04 to 0.12)
Age	0.01 (-0.08 to 0.10)	**0.08 (0.00 to 0.15)**	-0.04 (-0.13 to 0.04)	0.10 (-0.02 to 0.22)	**0.09 (0.01 to 0.18)**	0.05 (-0.05 to 0.14)
Weight	-0.04 (-0.13 to 0.05)	0.06 (-0.01 to 0.13)	0.01 (-0.09 to 0.10)	-0.03(-0.16 to 0.11)	0.09 (-0.00 to 0.18)	0.07 (-0.03 to 0.18)

Estimate and (95% CI). All estimates are based on log transformed outcome variables.

Continuous predictors (including pain intensity) were standardized before analysis. Statistically significant results are indicated in bold type.

Table 3.4: Model Comparisons.

	Predictor				Outcomes							
	Displacement		Velocity		Displacement				Velocity			
					Sagittal		Frontal		Sagittal		Frontal	
	Chi^2	P	Chi^2	P	Chi^2	P	Chi^2	P	Chi^2	P	Chi^2	P
n comparison	32		32		25		25		25		25	
TSK-11[a]	0.99	.32	0.90	.34	0.66	.42	3.13	.08	1.17	.28	7.14	**.008**
Fear sagittal					0.35	.55	0.26	.61	0.31	.58	1.27	.26
Fear frontal					4.35	**.04**	8.15	**.004**	0.93	.34	9.79	**.002**
Rel. direct. fear					9.47	**.002**	8.02	**.005**	0.39	.53	7.07	**.008**

Comparisons of the baseline model against the baseline model and an additional predictor describing fear. Log transformed models. Continuous predictors (including pain intensity) were standardized before analysis. Statistically significant results are indicated in bold type.

[a] TSK-11: Tampa Scale of Kinesiophobia 11 item version.

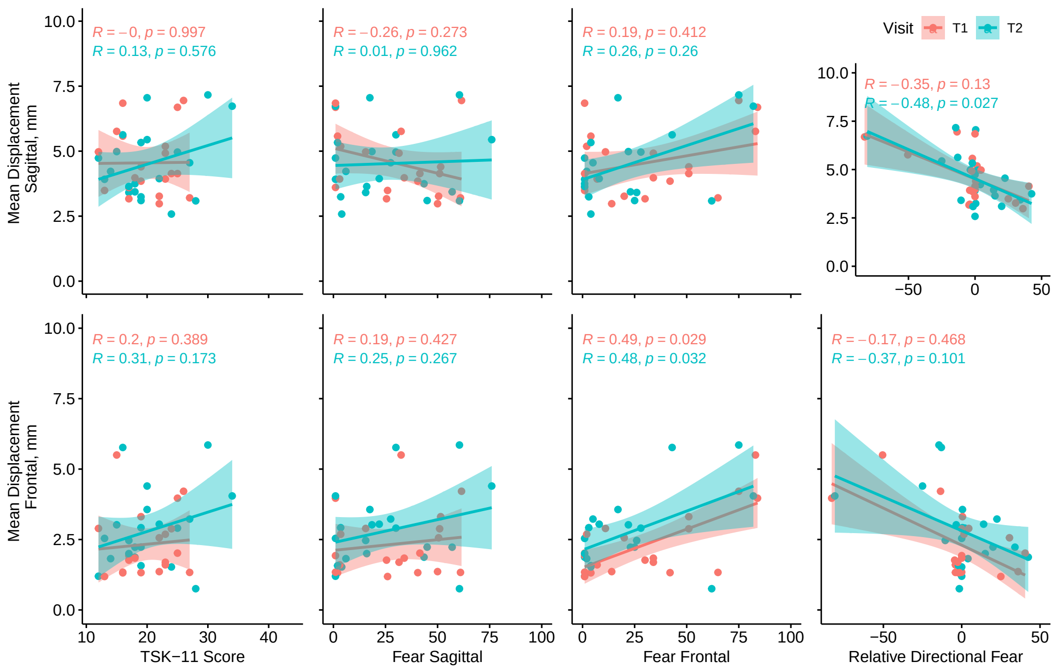

Figure 3.3: Displacement on the sagittal and frontal plane and fear variables. R values are spearman correlations. Negative values for relative directional fear show higher fear of frontal plane movements and positive values show higher fear of sagittal plane movements.

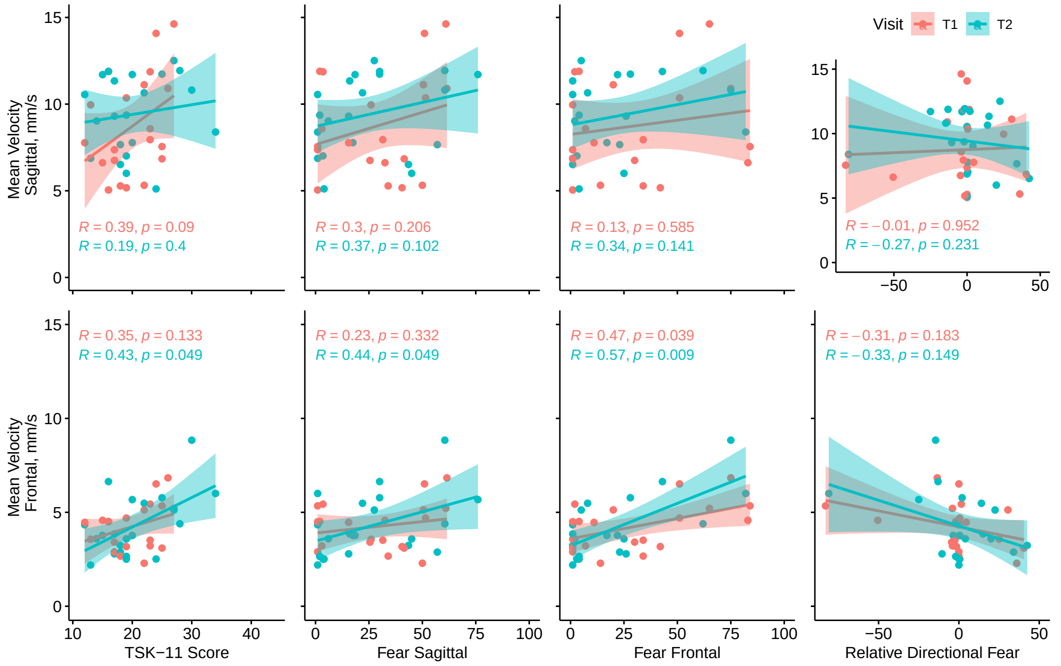

Figure 3.4: Postural sway velocity on the sagittal and frontal plane and fear variables. R values are spearman correlations. Negative values for relative directional fear show higher fear of frontal plane movements and positive values show higher fear of sagittal plane movements.

3.5 DISCUSSION

3.5.1 *Summary of results*

The TSK-11 as a general measure of fear was not related to undirected measures of balance, but was associated with velocity on the frontal plane. Fear of movement on the sagittal plane was not associated with any directional outcome, but fear measured for the frontal plane was associates with multiple directional measures. Velocity in the sagittal plane was not associated with any of the fear variables. When fear on the frontal plane was higher than fear on the sagittal plane, sway tended to be increased, whereas wen fear on the sagittal plane was larger than fear on the frontal plane, sway tended towards a decrease. This was the case in three of four direction specific outcomes.

3.5.2 *Discussion of results*

Our results suggest that fear of movement in the frontal plane, but not fear of movement in the sagittal plane, were relevant to postural balance. It has been proposed that during regular standing with approximately parallel feet, balance on the frontal plane relies on muscle contractions around the pelvis, whereas sway on the sagittal sway is regulated predominantly by contractions around the ankle (Winter, 1995). Based on this assumption we hypothesize that fear of torso movements in the frontal plane are more relevant to balance regulation, as fear from frontal plane movements may interfere with the use of the hip strategy. On the other hand, fear from sagittal plane movements may not interfere with the successful balance control at the level of the hip.

Other authors assumed that elevated fear might be linked to a decrease of balance parameters (Kiers et al., 2015; Mazaheri et al., 2013; Mazaheri et al., 2014). These assumptions are supported by the study of Shanbehzadeh et al. (2018) which suggested generally less sway in people with elevated fear in comparison with people with lower fear. In contrast, we found a general tendency towards larger displacements and higher velocity with an increase in fear measures. It could be argued that if people with LBP and high fear refrain from using an effective mechanism for balance regulation, balance could be compromised. This would be in line with Mok et al. (2004) who proposed that people with LBP could rely less on their hip for regulating sway and moreover remarked that fear might be a factor related to the limited control of sway by the hip. However, these assumptions remain speculative.

Values for relative directional fear were closely centered around zero. This suggests that the direction of movement with respect to fear seems to be only relevant for a smaller number of people. As a tendency, negative values (higher fear on the frontal plane) were associated with higher sway, while positive values (higher fear on the sagittal plane) were associated with less sway. These results may to some extent reflect the enlarged sway for people with fear in the frontal plane, but further work should clarify whether relative directional fear independently of the general level of fear plays a role for postural balance.

Other authors have argued that assessments of fear should be based on concrete movement examples rather than broader assessments (Leeuw et al., 2007) to detect associations with movement quality (Matheve et al., 2019; Pincus et al., 2010). The results of this study support this notion only partially, as also TSK scores were found to be significantly associated with sway velocity on the frontal plane. Although the results of the analyses were largely robust to the deletion of individual participants from the analyses, figures 3.3 and 3.4 show that the results seem to be determined largely by a small number of participants, and many participants reported no to very little fear for movements on both planes. Furthermore, many participants did not judge one movement direction as more harmful than the other. Hence, the distinction of fear from frontal or sagittal plane movements may only be relevant for a small number of people.

3.5.3 *Limitations*

Although we included 25 participants in the analysis of sway velocity and displacement and showed significant results that appeared to be reasonably reliable, the ICC estimates were calculated from a very low number of participants. We would expect to see stronger effects with a higher number of participants tested. More importantly, the data included in this study originated from participants with LBP who registered for a trial investigating an exercising intervention. Therefore, we might have the presence of a selection bias as for example only participants with lower levels of fear registered for the trial. Therefore, the results of our study need to be interpreted in the context of this subset of people with LBP.

To assess the direction specific fear, we had to introduce custom questions that did not originate from a validated questionnaire. It remains unclear whether it was adequate to use the mean of the flexion and extension question as a measure for fear of movements in the sagittal plane. Future studies may consider flexion and extension in the sagittal plane separately. However, no statistically significant association of fear for flexion or extension on the sagittal plane were found when the corresponding model comparisons were performed in addition.

When graphically inspecting direction specific fear (Figure 3.2), it became apparent that participants who reported more fear on the sagittal plane than on the frontal plane, had generally rather low fear. This may confound the analysis results for relative directional fear. Therefore, these results should be reproduced in another sample.

Another limitation refers to the variables that could be controlled for in this study. Additional questions referring to pain and how careful movements would be performed were assessed in the direction specific type as well. This data was collected, as it is important to discern how movements are avoided and how painful they are experienced (Pincus et al., 2010). Unfortunately, as we aimed to maintain the comparability of the baseline models between the different outcomes and as the available number of participants did not permit to include these estimates in our analysis, we could not control for pain caused by movements in different directions. It has been reported that pain did not account for the link found between fears and rather stiff movement of the spine (Christe et al., 2021), nevertheless future studies should control for pain on a movement specific and not only on a general level. Furthermore, several statistical tests were performed in this analysis and we did not adapt the significance thresholds to counteract an inflation of the error probability.

3.6 conclusion

People with LBP expressed higher values on different postural balance measures with higher fear for the frontal plane but not the sagittal plane. While the TSK-11 was not associated with general measures of postural sway, a positive relation to velocity on the frontal plane was found. The results suggest that it might be important to consider relative directional fear, although this concept needs to be further explored in future studies.

4 SENSOR BASED TRACKING OF RISK FACTORS FOR LOW BACK PAIN

In the second chapter we have presented an applied study on the effects of an intervention for people with LBP using sensors. First analyses across studies have shown that for app-based mHealth interventions in general, sensor data may provide a more powerful basis for adaptations than self-reports (Tong et al., 2021). In addition, smartphone sensors have already been used in people with LBP to provide interventions which take the present situation of the patient into account and can give hints when favourable circumstances arise to integrate physical activity (Rabbi et al., 2018). However, data from sensors could possibly be used to measure factors which could be related to pain. In this chapter we present a case study of an adolescent skier, who used a smartphone app which collected data from the phones sensors during almost one skiing season. Based on this data we suggest that monitoring of ski training could be accomplished by using standard mobile phones.

This chapter is based on the publication:
Spörri, Jörg⋆; **Meinke, Anita**⋆; Brogli, Luzius; Schwab, Patrick; Karlen, Walter. Sensor-based monitoring of on-snow ski practice using mobile phones: Case study of a young competing ski athlete. *in preparation* [1]

I have participated in the planning of the study, and conceptualization of the mobile app for this study. I planned the self-report data submitted through the mobile app, wrote the text presented in this thesis and conducted the analyses which are presented. The study and data collection of the larger project which included this sub-project was done by Jörg Spörri and his team. The collection of mobile phone data was planned together with Patrick Schwab, Walter Karlen, who supervised this work and Jörg Spörri. Michela Rimensberger and Patrick Schwab

1 ⋆ Authors contributed equally

programmed the smartphone app. The automated identification of dates including possible ski events before the manual labeling was provided by Luzius Brogli and Yanick Riederer.

4.1 TRACKING OF SKI TRAINING

4.1.1 *Background*

4.1.1.1 *Low back pain due to large physical stress in ski athletes*

A recent meta-analysis estimated the annual prevalence of LBP aggregated for different sport disciplines at 51%, although the authors pointed out potential biases (Wilson et al., 2021). Amount of training was most frequently found to be connected to LBP (Wilson et al., 2021). Even youngsters who compete in ski contests have degenerative alterations of the spinal column (Peterhans et al., 2020) and the knees (Fröhlich et al., 2020). Especially changes at the intervertebral discs have been related to elevated reporting of complaints (Peterhans et al., 2020) and for those issues due to "overuse", LBP was ranked as second most common (Schoeb et al., 2020). Large physical stress placed on the intervertebral discs in skiing turns is assumed to contribute to LBP, as the spinal column flexes on all three movement planes and may be exposed to higher forces (Spörri et al., 2015). Further, vibration during skiing develops in a frequency range the spine seems to be vulnerable for and is suspected to induce degenerative changes (Spörri et al., 2017).

4.1.1.2 *Sensor-based Technology in Ski Research*

Sensors have been used to describe movement in diverse sports, including even equitation and aquatics (Taborri et al., 2020). Specifically in ski research, IMUs (Kondo et al., 2012; Spörri et al., 2015; Spörri et al., 2017; Fasel et al., 2016; Matsumura et al., 2021), the global navigation satellite system (Fasel et al., 2016) and shoe inlays recording pressure (Matsumura et al., 2021; Spörri et al., 2015) have sometimes jointly been applied. The obtained data was used to describe joint configurations and body rotations (Kondo et al., 2012; Matsumura et al., 2021; Spörri et al., 2015), frequency content of vibrations (Spörri et al., 2017), pace and path of the center of mass (Fasel et al., 2016), weight distribution on the feet (Matsumura et al., 2021) and lateral comparability of movements (Matsumura et al., 2021). An overview of their adoption and resulting suggestions for further use has been offered in a review only recently (Supej and Holmberg, 2021). It was suggested that sensor-based approaches could deliver feedback and enhance sports performance, not only for competing athletes (Düking et al., 2017; Matsumura et al., 2021).

4.1.1.3 *Monitoring of ski training load*

The setups and systems as described above, have been used to describe individual runs and ski sessions. Simpler systems could quantify overall ski training load. A recent review summarizing data across different sport disciplines suggested that elevated training load in certain time spans can promote injury and hence encouraged regular assessment (Jones et al., 2017). Although Hildebrandt et al. (2021) did not confirm that the amount of overuse related injuries became more frequent with higher amount of training in young skiers, this expectation seems plausible. Hildebrandt et al. (2021) obtained their data from trainers in a ski school who estimated how demanding each class was. Such measures are limited as they are indirect and likely imprecise for the individual skier. In another setting, even if direct self-reports on the amount and duration of training would have been requested from each individual athlete, the actual time spent skiing might deviate substantially for similar training durations within and between athletes. Waiting times at different lifts and design of the ski area in general may cause differences in effective training time. Sensors could be well suited to allow a record ski training sessions, estimate the time that was actually spent skiing and even quantify the number of runs and turns performed. As excessive stress is thought to arise during turns (Spörri et al., 2015), estimating the number of turns could be a relevant parameter for predictions of injury and potentially help to adapt the training.

4.1.1.4 *Research Question*

In this work we propose that data from mobile phones could be used to quantify ski training and in the future maybe to assess the risk or quantify predictors for developing LBP. We present a case-study on an adolescent ski athlete who reported his ski-training and provided the sensor data from his mobile phone for several months.

4.1.2 *Method*

4.1.2.1 *Data collection*

Within a larger project, data from the same cohort as in (Fröhlich et al., 2020; Peterhans et al., 2020; Schoeb et al., 2020) was collected the year after. The ski athletes who decided to participate in the follow up study received an intervention consisting of exercises for injury prevention. Sensor data and corresponding self-reports about skiing were recorded by a customary designed smartphone app. The study was authorized by the cantonal ethics committee Zurich (BASEC 2018-01807) and the participants or their parents provided informed consent. In this thesis, exemplary data collected with the smartphone app of a single participant is presented.

4.1.2.2 *Smartphone App*

The smartphone app was developed for research purposes within the National Research Program 75 "Big Data" (167302). The app was designed for its capability to record data from different sensors, such as acceleration, speed and altitude based on the GPS signal. Besides the recorded sensor data, short self-report forms could be submitted. The app was conceptualized to allow the users to opt in for different "challenges". Each challenge consists in a relevant behavior the user commits to do for a certain period of time or amount of repetitions. The user registers his progress with the self-report function. The app then provides feedback i.e. the total amount of registered events on the home screen and simple comparisons with the whole group of other participants in a given challenge.

For the purpose of this case-study, altitude, speed and acceleration data were used. Data was only collected, when the phone moved and acceleration data was saved in chunks of 15 minutes, to keep the size of the files manageable. Recorded data was sent to a server when the phone was connected to wifi, and stored in a MongoDB (MongoDB Inc., New York City, USA) database. The credentials for login of the participants were stored separately from the data. A connection between the data from the app and other relevant study data was made by the participants reporting a token to the investigators that could be be accessed through the app. The self-report data presented here was collected as part of the "On Snow Challenge", which encouraged the participants to log their ski training sessions. Each report included 4 questions, prompting the participants to indicate the date and the start time of their ski session. Further the time effectively spent skiing in hours and minutes and the number of runs made were prompted.

4.1.3 *Data analysis*

Data analyses were conducted in MATLAB (MathWorks, Natick, USA) and R (R Core Team, 2021). Altitude and speed of the smartphone were derived from the database and cut to contain data per day only. Data which had many missing values, altitudes of zero, or did not include any altitude higher than 1700 meters or the speed was too low was discarded. Duplicate records were removed. Data without an altitude plateau was removed. Altitude was graphically displayed together with the acceleration data aggregated across axes. Each record received a rating into one of three categories, whether the ski event and individual runs were visible, skiing was visible, but not individual runs, or no skiing was visible on the record. Further, for each record the number of runs was counted, the onset and end of each run were manually labeled. From these labels, the actual ski time was calculated for each ski event. Descriptive statistics and graphs, Pearson correlation, Wilcoxon signed-rank test and Chi-square test as described by Field et al. (2012) were used. The R package gmodels (Warnes et al., 2018) was used for the Chi-square test. The accelerometer data was smoothed for the graphical visualization.

4.1.4 *Results*

4.1.4.1 *Manual Data Cleaning and Data Quality*

Based on the **sensor data**, a total amount of 69 records had been indicated as potentially containing ski events and were labeled. 3 invalid duplicate entries were removed. Of the remaining 66 ski events, 11 were discarded from further analyses, as the ski event was not clearly visible during manual labeling. Examples of events for all three categories are displayed in Figure 4.1. Of the remaining 55 events that were retained for further analysis 37 were labeled as showing ski events, but not individual runs, 18 were labeled as showing ski events and the individual runs. Similar to Figure 4.1 C, many events indicated that the phone was left at a change room and not carried on the body during the training.

Of the in total 66 **self-reports**, 4 were registered for dates which already had a report. One of these was verified as a date with two skiing sessions. Two of the duplicate reports were registered one month later than the event, which may indicate that the participant by mistake had selected the wrong month. All self-reports were retained for further analysis. For all reports the participant had indicated the date the report was registered for and the number of runs, but once the start time was missing and 6 times the estimated skiing duration was not reported. One entry contained an unlikely estimated ski duration of 796 minutes.

4.1.4.2 *Ski Events from both data sources*

A comparison of the ski events derived from self-reported data and manually labeled sensor data is shown in Figure 4.2. During the entire period, skiing was registered for 71 unique dates, with one date containing two separate ski sessions, which were visible in the sensor data and registered by self-report. On 45 of the 71 dates, skiing was indicated by the self-report and the labeled sensor data. For 17 of the self-reported dates, no corresponding sensor data could be obtained and for 9 of the dates with labeled sensor data, no skiing was reported. As indicated in the Figure, during the first month of study participation, most dates registered could also be detected in the sensor data. During the rest of the study there were more days during which the self-reports and data derived from the sensors did not agree.

4.1.4.3 *Identification of runs and turns*

For those records which had a complete estimates for the number of runs (n=15) and for the time spent skiing (n=12), correlations were calculated and are displayed in Figure 4.3. The graphs show that the number of runs correlated between the self-reported data and the estimates based on the generated sensor data labels, but not the estimated time spent skiing. There were no differences between the self-reported number of runs (median=14) and number of runs from sensor-data

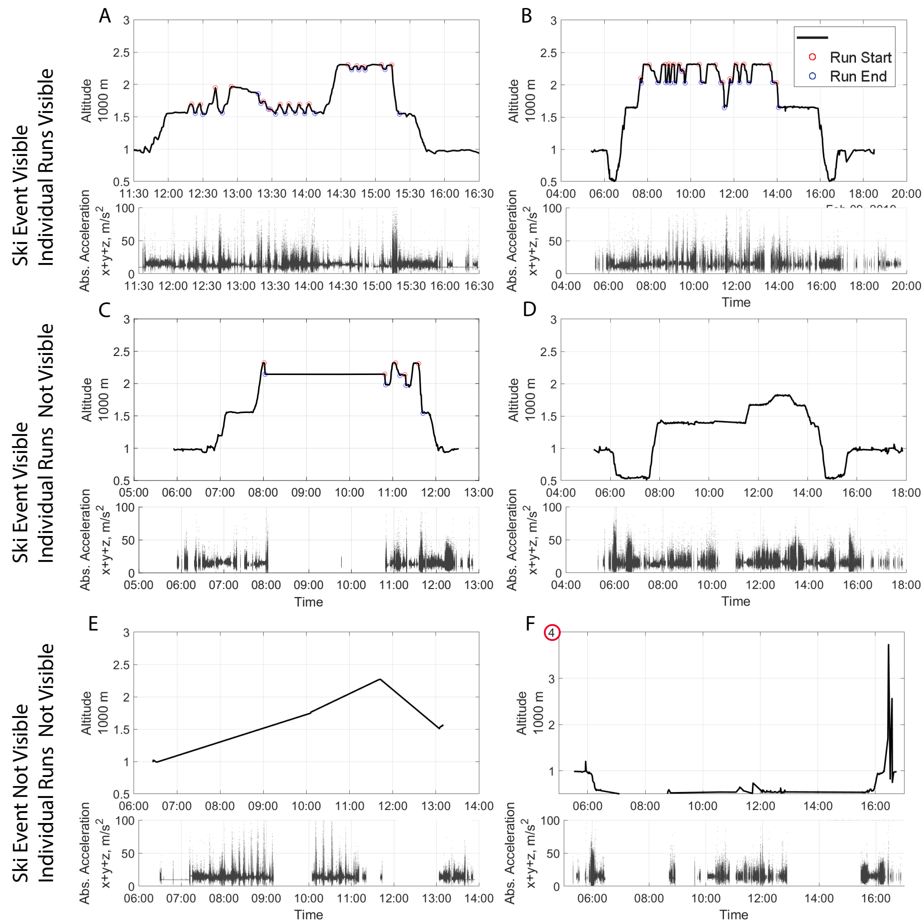

Figure 4.1: Altitude and acceleration for examples of ski events with different visibility ratings. A and B: Ski events and runs are visible. C and D: Ski events are visible, runs are not visible. E and F: Ski events and runs are not visible.

(median=14), p=.69, r=-.07 or the estimated skiing time between the self-report (median=70 minutes) and sensor data (median=78 minutes) p=.56, r=-.12. In Figure 4.4 the bottom graph shows the acceleration in between the start and end label of the first run in the graph on top. These data show that if the data is recorded at sufficient quality, the number of runs and turns could be identified.

4.1.4.4 *Late reporting of ski events*

Of all 66 self-reports, 39 were reported on the date of skiing and 27 at least 1 day later. The events reported later were registered at median during the following day. With the exception of two dates, where likely the wrong month had been selected,

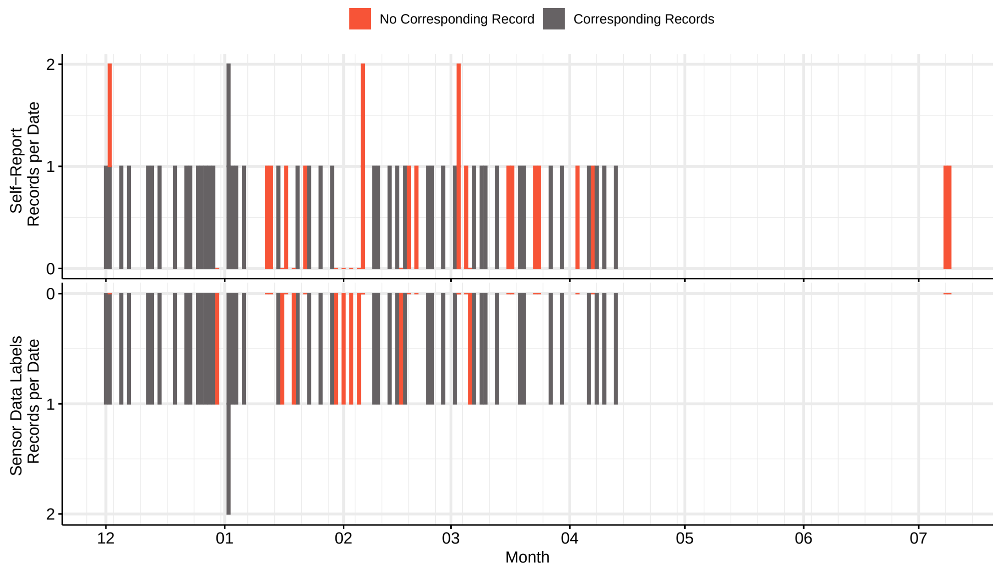

Figure 4.2: A, Ski events detected based on sensor data. B, Ski events reported.

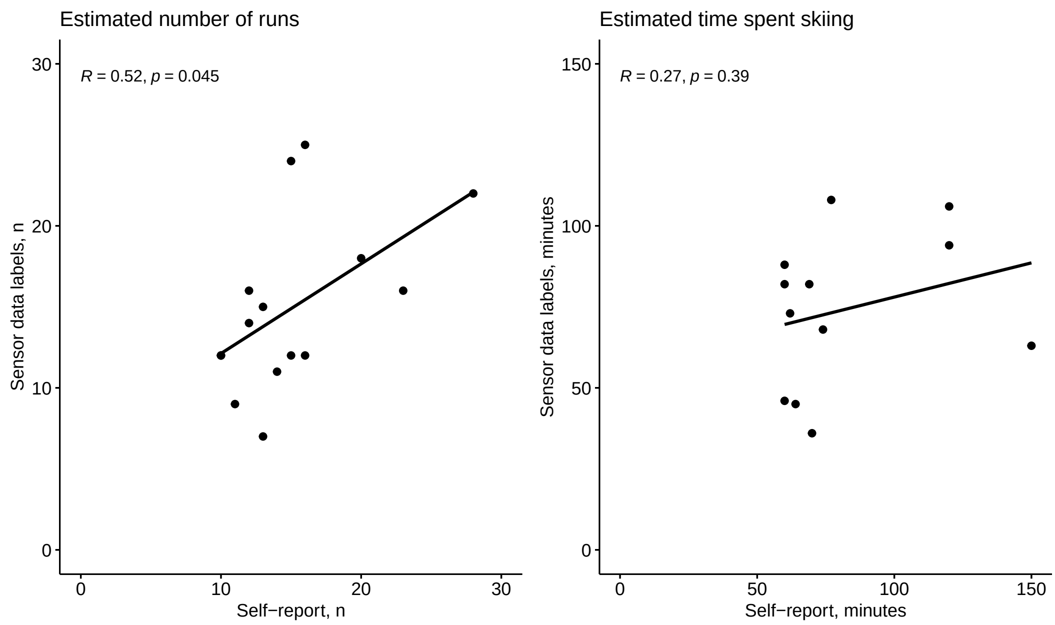

Figure 4.3: Pearson correlation of 12 Dates with visible ski events and runs and availables self-report data.

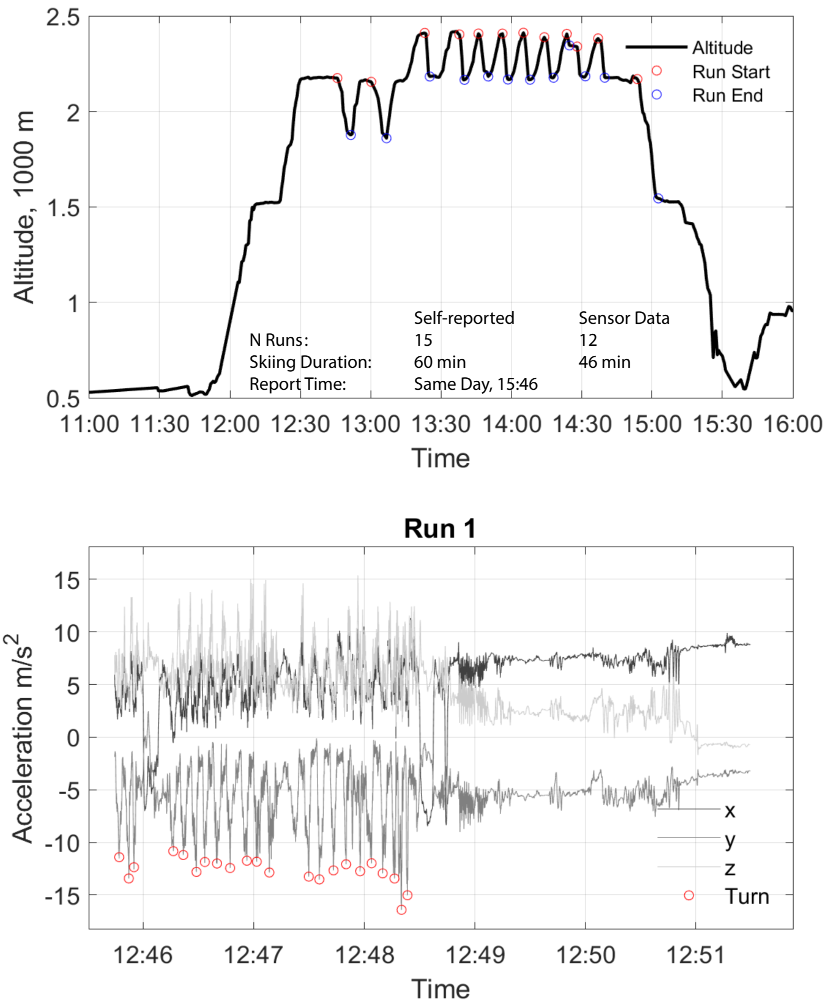

Figure 4.4: An ideal example of ski event detection based on altitude and acceleration and manual labels of Run start and End for individual ski runs.

the delayed reports occurred latest 5 days after the ski event. Table 4.1 shows how many corresponding ski events were detected, when the data was reported on the date of the event or later. If corresponding sensor data had been obtained or not was related to whether the ski event was manually registered for the current date or had been registered late $\chi^2(1)=6.89$, $p=.009$. The odds ratio of 4.1 (CI: 1.23, 15.22) indicates that there was a higher chance of not finding corresponding sensor data, when the self-report was submitted on a later date.

Table 4.1: Number of self-reports, for which sensor data is available, depending on whether the self-report was registered on the same date as the ski event or later.

	Corresponding Sensor Data		
Report date	Not Available	Available	Row sum
Later report date than ski event	13	14	27
The same date as ski event	7	32	39
Total	20	46	66

4.1.5 *Discussion*

In this chapter, we proposed that amount of training could be monitored using on sensors available in mobile phones as an indicator for the training load from on-snow practice in adolescent ski athletes. This data can be helpful to learn more about the development of overuse injuries in this population and possibly help to improve the management of training load to prevent injuries. Based on the data presented in this case study, three aspects stand out.

1. **Technical requirements need to be satisfied consistently**. Sensor data collected from an uncontrolled setting are frequently less accurate than data collected in an experimental setting and neither the identification of potential error sources is trivial. As seen in the data from this case-study, for several days altitude and speed data derived from the GPS signal were missing and therefore render the available data incomplete. In a remote setting the circumstances under which flawed data are obtained might be unknown, and developers of such systems might not have access to affected devices. Although many potential challenges could be circumvented by rigorous testing of the system, and online algorithms could be used to detect difficulties early on, maintenance of the system will likely require continuous effort

to ensure completeness and quality of such data. For example updates of operating systems could make adaptation of such an app necessary.

2. **Both, self-report and passive activity tracking methods require active engagement of the athlete**. Even though making use of the phones built in sensors seems perfectly effortless at a first glance, minimal actions are still required from the user. The phone still has to be brought to the training site and carried on the body throughout skiing. Based on the data we obtained, it was suspected that the phone might have been frequently left in a change room (e.g. Figure 4.4 C), instead of being worn with the training suit. The actual ski session was not recorded in those cases, but time on the mountain still could be captured. Bringing the phone has to be remembered right before the training, other than with self-reports which could be submitted at any time after the training. Especially at the beginning of the tracking period, for most self-reports corresponding sensor data was available, which might be a sign for consistent reporting and use of the app. However, there also were events registered which had no corresponding self-report data, indicating that the sensors provided additional information regarding dates with training over the self-reported data. On the other hand, not all events that were included in the self-reported data were recorded by the sensors. In order to enhance engagement of users outside of a research setting, users could be provided with more detailed and engaging feedback besides the simple comparisons available in this study. Such feedback could increase the engagement and motivation of the users.

3. **Provided 1. and 2. are satisfied, the data is suitable to provide detailed estimates on the number of ski events, duration of runs and to estimate the number of turns**. As can be seen in the graphs showing details of records in good quality, this data would be suitable to quantify the actual ski time based on extracting individual runs and furthermore the number of turns performed during each run could be estimated.

The data presented above outlines how training load could be monitored to use this data for the prevention of LBP in ski athletes. This data was collected for research purposes and only minimal feedback was provided to the athlete, to not bias the results. However, when developing such a system, more informative feedback could increase the engagement of athletes. In addition, as concluded by Düking et al. (2018), care should be taken that the statistics offered to athletes actually add value to sport practice or prevention. For example, although vibration during skiing has been proposed to play a role in LBP of athletes, the causal association is yet to be confirmed (Spörri et al., 2017). For such applications of not only sensor-based methods, the objective should be made explicit and the data should be protected, as athletes may have reservations that such information could affect their admission to contests (Rönnby et al., 2018). A limitation of this study is that the definition of what constitutes a run was not clearly defined in advance and may have differed between the athlete and the investigators. Further, manual labels were based on altitude alone. Although biases in self-reported data are well known, athletes may be able to fairly accurately estimate the time spent skiing, if they are able to recall the number of runs correctly. Run times have a high relevance for the sport and are frequently communicated, thus self-reported estimates on the scale of individual runs could be of comparatively high quality.

In conclusion, skiing was in general distinctly visible on the data collected from smartphone sensors and unobtrusive monitoring of ski training should be possible based on such data, although in our study not all reported ski events could be captured. An app which monitors skiing based on sensor data, but possibly offers the complementary option to record sessions manually may account for these shortcomings, and be suitable for use by adolescent athletes. In addition, information which is harder to obtain from self-reports, such as the number of turns performed could enrich data which has been more commonly used.

5 DISCUSSION AND CONCLUSION

5.1 DISCUSSION

5.1.1 *Summary of the work*

This thesis presents different contributions to study LBP with mobile sensors. Through a RCT we concluded that exercising with feedback from wearable sensors did not improve balance during a static standing task. As the results for lumbar spine movement exhibited an unexpected tendency opposing the predicted direction, clarification in further studies is required. When we analyzed the effect of fear of movement on postural balance when standing on a sensorized platform, an effect on the frontal plane but not on the sagittal plane was observed. In addition, the investigation showed an indication that relatively stronger fears on the frontal plane were related to higher sway, while relative to stronger fears on the sagittal plane resulted in slightly reduced sway. We also illustrated that mobile sensors can be used to track risk factors. We generated example data for adolescent athlete skiers and present a case study that showed the feasibility of using such data to estimate the amount of ski training. When the data quality was good, skiing events and even individual turns could be identified clearly.

Nevertheless, the findings were limited by the nature of the sampled data. To a large extend the conducted studies relied on sampling in free living conditions without tight control of experimental conditions, leading to challenges in data quality with limited adherence and sample sizes. Therefore, it is important to note that even passive tracking systems, such as the smartphone in the ski study and not only self-report training diaries depend to a large extent on the motivation and adherence of the user to obtain high quality data. As highlighted by our descriptive analyses of the adherence to the intervention in the RCT, the adherence was much higher when participants had received precise instructions on how to exercise compared to when they were free to exercise according to their choosing.

5.1.2 *Exercising with wearable sensors*

In chapter 2 we investigated whether a digital intervention which relied on sensor-based feedback to improve the movement capabilities of the torso may affect postural balance during quiet standing. For this intervention we have not observed an effect on the primary or secondary outcomes.

Although similar interventions have been the subject of other studies before (Alemanno et al., 2019; Matheve et al., 2018b; Hügli et al., 2015; Magnusson et al., 2008; Kent et al., 2015), our RCT strengthens the current evidence by investigating postural sway as a primary outcome. To our knowledge, this had not yet been explored. In addition, we used a randomized study design, which had only been the case in some of the mentioned studies (Hügli et al., 2015; Magnusson et al., 2008; Kent et al., 2015). Moreover, increasing the independence of people with LBP from clinicians and a therapeutic setting is an important motivation for the development of mHealth tools. The results presented in this study refer to exercises that were performed detached from a supervised, clinical context. These exercises were the only intervention provided to the participants. Apart from the exercise during the instructions, all exercises were done by the participants individually at home. Thus, the results have to be viewed in the context of the study that allowed little direct supervision, low dose of planned exercise, and the low adherence of some participants. Even the participants included in the per-protocol analysis did not fully comply with the schedule. The results obtained thus may underestimate effects that could be achieved under ideal and possibly under supervised conditions. In addition, other sensor-based interventions may have produced different findings.

With respect to movement outcomes, the assessment of postural balance during still standing may only indirectly capture changes in coordination of the torso, and not sufficiently sensitive to subtle changes at this level. In fact, a meta-analysis summarizing how exergames affect balance in elderly participants did not confirm an effect on measurements from a force platform during standing, but found an effect for other clinical assessments (Fang et al., 2020). Outcomes more closely related to the practiced tasks may have been better suited to capture an effect. However, choosing direct performance outcomes, as for example in the study of Jansen-Kosternik et al. (2013), would have added less scientific value. In line with this argumentation, movement of the lumbar spine during the motor control tasks, which required less transfer from the tasks that had been practised, showed a tendency towards change. However, this tendency was not in the predicted direction.

The questionnaire based assessments for the described study were chosen by taking into consideration a typical group of variables and tools (Chiarotto et al., 2015; Chiarotto et al., 2018), which have been recognized as essential for studies investigating LBP. This basic group of variables is intended to enhance the comparability among studies (Chiarotto et al., 2015; Chiarotto et al., 2018) and are partially shared with the outcomes which have been reported in reviews of exercising interventions (Hayden et al., 2005; Middelkoop et al., 2010; Saragiotto et al., 2016). Their conclusions showed that exercising improves chronic LBP (Middelkoop et al., 2010; Saragiotto et al., 2016), although the effects have been referred to as clinically relevant in only one of these reviews (Saragiotto et al., 2016), and in another review (Hayden et al., 2005) as probably relevant among patients rather than other people with LBP. Lately published substantial effect sizes for exercising interventions for people with LBP (Owen et al., 2020) have prompted harsh criticism and were seen as too high and unrealistic by authors of earlier reviews (Maher et al., 2021). Further, when considering exercises with electronic devices, Matheve et al. (2017) stated that the overall effectiveness was restricted. As Dario et al. (2017) stated in the context of telehealth studies in people with LBP, comprising largely of trials using web-pages or phone calls that the success may have been restricted by inherent limitations of the interventions which are transferred into the digital space. The situation with respect digital tools in LBP may be comparable to what was implied by this general comment. With this literature in mind, the results obtained for self-reported variables in the described RCT seem plausible.

5.1.3 *Understanding of LBP*

Problem solving generally becomes easier, the better the problem is understood. The same should be the case for LBP, about which there is still much left to learn. Maher et al. (2017) noted that knowledge of LBP needs to improve to provide interventions addressing the roots of LBP and Van Dieën et al. (2017) made a similar point for research in motor control in particular. In accordance with this, the less the relevant mechanisms have conclusively be clarified, the more difficult it will be to design efficient technological tools that provide an effect as intended. The more we know how LBP develops and which mechanisms are involved, the easier it may be to design effective systems.

With respect to the intended estimation of training load presented in chapter 4, the better processes leading to LBP due to intensive training are understood, the more precisely they can be assessed and better health management decisions can be made. As it has been suggested that the turns made during skiing may contribute to the onset of LBP by placing large strain on the spine (Spörri et al., 2015) and the quantification of turns in an automated manner seems feasible, making such data accessible to athletes and their coaches may be valuable. A tool like this may not only assist the management of training load in athletes, but could at the same time provide data for research to advance the understanding of the mechanisms leading to the development of LBP. To validate the assumption that turns could be problematic for the back (Spörri et al., 2015), longitudinal data recorded by smartphone sensors could be used, if a sufficiently high data quality can be ensured.

5.1.4 *Addressing fear through digital interventions*

MHealth interventions can play an important a role for LBP that goes further than facilitating the learning of movement skills, as it was discussed by Tack (2021) for virtual reality applications. Catastrophic thoughts can for example be addressed by graded exposure training (Uralde-Villanueva et al., 2016), and exposure through a virtual reality setup has been explored by Thomas et al. (2016). The declared aim of their study was to expose people to larger movement of the back, who had LBP and were pre-selected to also have elevated fear (Thomas et al., 2016). In our study fear did not change as a consequence of exercising. However, only an assessment for general fear, and not the assessments distinguishing movement planes were used. Similarly to the arguments made in the section above, a better understanding of fear in the context of LBP will help to design better interventions for this purpose. Delineating how far the impact of fear on motor control reaches is essential to know what may be expected of interventions that alleviate fears.

5.1.5 *Adherence to technology*

Mobile health technology can enhance interventions in different ways. The technology could transfer interventions to a different context, make contents accessible remotely, simplify certain tasks, or provide interventions in a more appealing manner. In addition, mobile technology can provide entirely new information to the user.

One of the challenges that is hoped to improve with the use of technology is the consistency in the use of interventions. In this thesis, for both the applications presented in chapter two and chapter four, challenges with respect to adherence were observed. The inconsistent use of the intervention in chapter two was likely detrimental to the effect of the intervention, and to the tracking application in chapter four strictly limiting the usefulness of the information which could be obtained. Thus we conclude in agreement with Matheve et al. (2017) that the use of technology driven solutions by itself does not guarantee acceptable uptake and compliance with a schedule. In the case of the ski tracking app, the phone needs to be carried during active skiing to capture for example the number of runs and turns. However, a review including elderly study participants found marginally superior adherence in participants who used interventions with a digital module or gaming intervention for exercising (Valenzuela et al., 2018).

In contrast to many other studies, the intervention had been performed at home, making it harder to obtain good quality data on exercise adherence. However, also in contrast to many studies, adherence was determined based on the log of the app. This may be an advantage, as in a study of Nicolson et al. (2018) frequent training activity was reported in manually completed diaries, even when sensor data implied that the participants had done much fewer exercises. It is not possible to draw the conclusion whether the presentation of the intervention as a game had a positive impact on adherence. Nevertheless, inclusion of gaming elements is not the only possible mode by which adherence could be improved. Other features might be able to improve adherence in the future and should be implemented and explored. The placement of scheduling features to make them more salient and less dependent on the initiative by the user should be considered. For the tracking of training as it was presented in chapter four, reminder messages to take the phone for the actual ski training when crossing certain altitude thresholds might have improved the data quality.

5.2 Limitations

Within the given timeframe to complete a thesis it is impossible to cover the whole area of technology based approaches in LBP and to keep up with the speed of novel developments. Therefore, this thesis can only provide a focused view on different branches of this area.

The RCT presented in chapter two had several limitations. Some difficulties arise from the small number of participants who could be reached. A part of the barrier towards participation may have been that people need to be made aware of technological management approaches, and see them as an option for themselves. Otherwise, people with LBP would likely not register for a study based on an advertisement, if they are not contacted directly. This may be similar for technology for LBP that is already available. If people are not aware that technological systems could be an option to manage their LBP, they will likely turn to more conventional treatment approaches and not actively seek these options. Further, we tried to recruit participants who manage LBP themselves and have not recently been in any therapy. A large number of these people may thus be satisfied with their personal solutions or for other reasons not be seriously interested in taking any immediate action against their LBP. In combination with the low adherence of some participants this could have been insufficient to show an effect of the intervention. Therefore, in future studies with a similar setup, it could be considered to relax the inclusion criteria to include more participants into the study. Further, the overall participant burden could be reduced for example by minimizing the amount of variables and removing the second pretest assessment. To some participants the burden from the study due to additional assessments which are not mentioned in this text, may have been too high and might have caused some participants to withdraw from the study. In the analyses presented in chapter three, a main limitation is the use of questionnaires for which the psychometric properties are unknown. Further validating studies and a confirmation of the concept of relative directional fear would be required in a next step.

During the conduction of the studies we learned that despite the pervasiveness of sensors obtaining data of good quality from these sensors can be challenging, especially in the field as in chapter 4. Difficulties with data quality were only detected late, as it was due to the large amount of data impossible to sift through the data to detect any difficulties in an ongoing data collection. In context where not only aggregates across people have to be of reasonable quality, but where information collected is the basis for informing a user on an individual level, high data quality is essential. On the other hand with the remote use of mobile devices makes it harder to ensure good data quality.

5.3 OUTLOOK

As the pilot study did not show any signs for an intervention effect on postural balance, no larger RCT with the same specifications is required. Instead, the focus of new studies should go towards the exploration of other outcomes that could not be covered in this study, or could take a closer look on the tasks which were already assessed. For instance, the intervention effect on the motor control tasks could be analyzed with respect to speed, as LBP is associated with a reduction in speed of such movements (Laird et al., 2014). Assessments of postural balance may benefit in the future from automated video- or audio instructions, to increase the degree of standardization, as comments from investigators can affect postural balance (Villa-Sánchez et al., 2019). The investigators responsible for conducting assessments might still be present to assure the correct task execution and provide further clarification and guidance if needed. In addition, tasks involving dynamic movement of the spine, or an assessment of re-position error may be worthwhile to explore in additional studies. As highlighted above targeted assessments should be incorporated to adequately capture fears of individual movements. Considering the intervention, the effect on fear of movement was only tested with the TSK-11 (Rusu et al., 2014; Woby et al., 2005), but not with the specific questions referring to trunk movements on different planes. This would link the fear assessment more closely to the exercises and could be more sensitive to elicited changes than a global assessment of fear of movement. In addition, future studies may prioritize high adherence in this context to estimate an intervention effect under ideal conditions and take additional measures to ensure adherence. As ultimately no exercising program can be effective which is not used, solutions to improve adherence which can be sustained in self-directed use of a technology should be preferred, such as the change in the scheduling options as mentioned in chapter two. More data and work is needed to make effective use of novel analysis techniques which require large-scale data collection and so far were only scarcely put into use to address important challenges in the field (Tagliaferri et al., 2020). Sensors might play a large role in providing this data and to facilitate learning more about LBP.

Considering the research presented in chapter three, the next necessary steps would be a validation of the items and a replication of the derived data. It should be clarified, whether the direction of fear is really just relevant to a few people, and maybe it could be investigated, if these specific fears are linked to differences in pain occurrence.

With respect to the passive monitoring of athletes' ski training, the development or possibly adaptation of suitable algorithms to detect ski events and turns automatically may be the obvious next step. Additional requirements of such systems from the viewpoint of users and other stakeholders should be investigated. As for example Rönnby et al. (2018) have investigated user opinions about an electronic load monitoring system for people in running sports. But not only for ski athletes, also for other people who already have or are at risk for LBP similar systems could be developed. Sensor data derived from phones may help to detect differences between people with and without pain, or those who develop LBP over time. Some differences between these groups may be hard to detect using other, laboratory based or less intensive assessment methods. Also an extension towards interventions directly provided through the smartphone become more and more practicable, as for example demonstrated by Rabbi et al. (2018).

5.4 CONCLUSIONS

Although we found that exercising with wearable sensors was not effective in improving movement or patient reported outcomes in people with LBP, digital tools offer a large quantity of possibilities, many of which have not yet been explored. Technological progress is ongoing and with this progress, the amount of unexplored possibilities may even keep increasing. In addition, the use of devices for the continuous monitoring will generate data which can further help to validate or dismiss current assumptions about long-term processes involved in LBP. The limited insights to LBP remain a restraining factor, but advances have been made. As the understanding of motor control and other aspects increases, better technological solutions can be designed to bring this knowledge and its application to people.

CURRICULUM VITAE

Anita Meinke

14.12.1990

Education

Doctor of Science, ETH Zürich, Switzerland 2017 - 2021

Master of Science, Psychology, University Koblenz-Landau, Germany 2013 - 2017

Bachelor of Science, Psychology, University Koblenz-Landau, Germany 2010 - 2013

Publications

Spörri, Jörg; **Meinke, Anita**; Brogli, Luzius; Schwab, Patrick; Karlen, Walter. Sensor-based monitoring of on-snow ski practice using mobile phones: Case study of a young competing ski athlete. *in preparation*

Meinke, Anita; Maschio, Cinzia; Meier, Michael; Swanenburg, Jaap; Karlen, Walter. The Association of Fear of Movement and Postural Balance in People with Low Back Pain. *in preparation for submission*

Meinke, Anita; Peters, Rick; Knols, Ruud; Swanenburg, Jaap; Karlen, Walter. *Feedback on Trunk Movements from an Electronic Game to Improve Postural Balance in People With Unspecific Low Back Pain: A Pilot Randomized Controlled Trial*, *(under review in JMIR Serious Games)*

Meinke, Anita; Peters, Rick; Knols, Ruud; Karlen, Walter; Swanenburg, Jaap. (2021). Exergaming Using Postural Feedback From Wearable Sensors and Exercise Therapy to Improve Postural Balance in People With Non-specific Low Back Pain: Protocol for a Factorial Pilot Randomized Controlled Trial. *JMIR Research Protocols*

10.8 (e26982)

Meinke, Anita; Hawighorst, Maren; Wagner, Andreas; Trojan, Jörg; Schweiker, Marcel. (2017). Comfort-related feedforward information: occupants' choice of cooling strategy and perceived comfort. *Building Research and Information 45.1–2 (pp.222-238)*

BIBLIOGRAPHY

Alazba, Amal, Hend Al-Khalifa, and Hana AlSobayel (2019). "RabbitRun: An Immersive Virtual Reality Game for Promoting Physical Activities Among People with Low Back Pain." In: *Technologies* 7.1, 2.

Alemanno, Federica, Elise Houdayer, Daniele Emedoli, Matteo Locatelli, Pietro Mortini, Carlo Mandelli, Alberto Raggi, and Sandro Iannaccone (2019). "Efficacy of virtual reality to reduce chronic low back pain: Proof-of-concept of a non-pharmacological approach on pain, quality of life, neuropsychological and functional outcome." In: *PLoS ONE* 14.5, e0216858.

Alsubaie, A. M., E. Martinez-Valdes, A. M. De Nunzio, and D. Falla (2021). "Trunk control during repetitive sagittal movements following a real-time tracking task in people with chronic low back pain." In: *Journal of Electromyography and Kinesiology* 57, 102533.

Alzahrani, Hosam, Martin Mackey, Emmanuel Stamatakis, Joshua Robert Zadro, and Debra Shirley (2019). "The association between physical activity and low back pain: a systematic review and meta-analysis of observational studies." In: *Scientific Reports* 9.1, 8244.

Areeudomwong, Pattanasin and Vitsarut Buttagat (2019). "Proprioceptive neuromuscular facilitation training improves pain-related and balance outcomes in working-age patients with chronic low back pain: a randomized controlled trial." In: *Brazilian Journal of Physical Therapy* 23.5, pp. 428–436.

Bakeman, Roger (2005). "Recommended effect size statistics for repeated measures designs." In: *Behavior Research Methods* 37.3, pp. 379–384.

Bates, Douglas, Martin Mächler, Ben Bolker, and Steve Walker (2015). "Fitting Linear Mixed-Effects Models using lme4." In: *Journal of Statistical Software* 67.1, pp. 1–48. arXiv: 1406.5823.

Berenshteyn, Yevgeniy, Kelsey Gibson, Gavin C. Hackett, Andrew B. Trem, and Mark Wilhelm (2019). "Is standing balance altered in individuals with chronic low back pain? A systematic review." In: *Disability and Rehabilitation* 41.13, pp. 1514–1523.

Bordeleau, Martine, Alexander Stamenkovic, Pier Alexandre Tardif, and James Thomas (2021). "The Use of Virtual Reality in Back Pain Rehabilitation: A Systematic Review and Meta-Analysis." In: *The Journal of Pain*.

Carvalho, Flávia A., Chris G. Maher, Marcia R. Franco, Priscila K. Morelhão, Crystian B. Oliveira, Fernanda G. Silva, and Rafael Z. Pinto (2017). "Fear of Movement Is Not Associated With Objective and Subjective Physical Activity Levels in Chronic Nonspecific Low Back Pain." In: *Archives of Physical Medicine and Rehabilitation* 98.1, pp. 96–104.

Casonatto, Juliano and Cárita Mayume Yamacita (2020). "Pilates exercise and postural balance in older adults: A systematic review and meta-analysis of randomized controlled trials." In: *Complementary Therapies in Medicine* 48, 102232.

Cavaleri, Rocco, Lucy S. Chipchase, Hugo Massé-Alarie, Siobhan M. Schabrun, Muath A. Shraim, and Paul W. Hodges (2020). "Corticomotor reorganization during short-term visuomotor training in the lower back: A randomized controlled study." In: *Brain and Behavior* 10.8, e01702.

Chen, Mingrong, Tingting Wu, Meina Lv, Chunmei Chen, Zongwei Fang, Zhiwei Zeng, Jiafen Qian, Shaojun Jiang, Wenjun Chen, and Jinhua Zhang (2021). "Efficacy of mobile health in patients with low back pain: Systematic review and meta-analysis of randomized controlled trials." In: *JMIR mHealth and uHealth* 9.6, e26095.

Chiarotto, Alessandro, Maarten Boers, Richard A. Deyo, Rachelle Buchbinder, Terry P. Corbin, Leonardo O.P. Costa, Nadine E. Foster, Margreth Grotle, Bart W. Koes, Francisco M. Kovacs, C. W. Christine Lin, Chris G. Maher, Adam M. Pearson, Wilco C. Peul, Mark L. Schoene, Dennis C. Turk, Maurits W. Van Tulder, Caroline B. Terwee, and Raymond W. Ostelo (2018). "Core outcome measurement instruments for clinical trials in nonspecific low back pain." In: *Pain* 159.3, pp. 481–495.

Chiarotto, Alessandro, Richard A Deyo, Caroline B Terwee, Maarten Boers, Rachelle Buchbinder, Terry P Corbin, Leonardo O P Costa, Nadine E Foster, Margreth Grotle, Bart W Koes, Francisco M Kovacs, Chung-Wei Christine Lin, Chris G Maher, Adam M Pearson, Wilco C Peul, Mark L Schoene, Dennis C Turk, Maurits W Van Tulder, and Raymond W Ostelo (2015). "Core outcome domains for clinical trials in non-specific low back pain." In: *European Spine Journal* 24.6, pp. 1127–1142.

Chiarotto, Alessandro, Lara J. Maxwell, Raymond W. Ostelo, Maarten Boers, Peter Tugwell, and Caroline B. Terwee (2019). "Measurement Properties of Visual Analogue Scale, Numeric Rating Scale, and Pain Severity Subscale of the Brief Pain Inventory in Patients With Low Back Pain: A Systematic Review." In: *Journal of Pain* 20.3, pp. 245–263.

Chiarotto, Alessandro, Leo D. Roorda, Martine H. Crins, Maarten Boers, Raymond W. Ostelo, and Caroline B. Terwee (2020). "PROMIS Physical Function Short Forms Display Item- and Scale-Level Characteristics at Least as Good as the Roland Morris Disability Questionnaire in Patients With Chronic Low Back Pain." In: *Archives of Physical Medicine and Rehabilitation* 101.2, pp. 297–308.

Christe, Guillaume, Geert Crombez, Shannon Edd, Emmanuelle Opsommer, Brigitte M. Jolles, and Julien Favre (2021). "Relationship between psychological factors and spinal motor behaviour in low back pain: a systematic review and meta-analysis." In: *Pain* 162.3, pp. 672–686.

Ciabattoni, Lucio, Francesco Ferracuti, Giuseppe Lazzaro, Luca Romeo, and Federica Verdini (2016). "Serious gaming approach for physical activity monitoring: A visual feedback based on quantitative evaluation." In: *2016 IEEE 6th International Conference on Consumer Electronics - Berlin, ICCE-Berlin*. Berlin: IEEE, pp. 209–213.

Costa, Luciola Da C.Menezes, Christopher G. Maher, James H. McAuley, Mark J. Hancock, and Rob J.E.M. Smeets (2011). "Self-efficacy is more important than fear of movement in mediating the relationship between pain and disability in chronic low back pain." In: *European Journal of Pain* 15.2, pp. 213–219.

Dario, Amabile Borges, Anelise Moreti Cabral, Lisandra Almeida, Manuela Loureiro Ferreira, Kathryn Refshauge, Milena Simic, Evangelos Pappas, and Paulo Henrique Ferreira (2017). "Effectiveness of telehealth-based interventions in the management of non-specific low back pain: a systematic review with meta-analysis." In: *The Spine Journal* 17.9, pp. 1342–1351.

Dieën, Jaap H van, N Peter Reeves, Greg Kawchuk, Linda R. Van Dillen, and Paul W Hodges (2019). "Motor Control Changes in Low Back Pain: Divergence in Presentations and Mechanisms." In: *Journal of Orthopaedic and Sports Physical Therapy* 49.6, pp. 370–379.

Ditchburn, Jae-Llane, Paul van Schaik, John Dixon, Alasdair MacSween, and Denis Martin (2020). "The effects of exergaming on pain, postural control, technology acceptance and flow experience in older people with chronic musculoskeletal pain: a randomised controlled trial." In: *BMC Sports Science, Medicine and Rehabilitation* 12, 63.

Dixon, William G., Anna L. Beukenhorst, Belay B. Yimer, Louise Cook, Antonio Gasparrini, Tal El-Hay, Bruce Hellman, Ben James, Ana M. Vicedo-Cabrera, Malcolm Maclure, Ricardo Silva, John Ainsworth, Huai Leng Pisaniello, Thomas House, Mark Lunt, Carolyn Gamble, Caroline Sanders, David M. Schultz, Jamie C. Sergeant, and John McBeth (2019). "How the weather affects the pain of citizen scientists using a smartphone app." In: *npj Digital Medicine* 2, 105.

Düking, Peter, Hans-Christer Holmberg, and Billy Sperlich (2017). "Instant Biofeedback Provided by Wearable Sensor Technology Can Help to Optimize Exercise and Prevent Injury and Overuse." In: *Frontiers in Physiology* 8, 167.

Düking, Peter, Christian Stammel, Billy Sperlich, Shaun Sutehall, Borja Muniz-Pardos, Giscard Lima, Liam Kilduff, Iphigenia Keramitsoglou, Guoping Li, Fabio Pigozzi, and Yannis P. Pitsiladis (2018). "Necessary steps to accelerate the integration of wearable sensors into recreation and competitive sports." In: *Current Sports Medicine Reports* 17.6, pp. 178–182.

Fang, Qun, Parisa Ghanouni, Sarah E. Anderson, Hilary Touchett, Rebekah Shirley, Fang Fang, and Chao Fang (2020). "Effects of Exergaming on Balance of Healthy Older Adults: A Systematic Review and Meta-analysis of Randomized Controlled Trials." In: *Games for Health Journal* 9.1, pp. 11–23.

Fasel, Benedikt, Jörg Spörri, Matthias Gilgien, Geo Boffi, Julien Chardonnens, Erich Müller, and Kamiar Aminian (2016). "Three-dimensional body and centre of mass kinematics in alpine ski racing using differential GNSS and inertial sensors." In: *Remote Sensing* 8.8, 671.

Ferreira, Manuela L., Gustavo Machado, Jane Latimer, Christopher Maher, Paulo H. Ferreira, and Rob J. Smeets (2010). "Factors defining care-seeking in low back pain - A meta-analysis of population based surveys." In: *European Journal of Pain* 14.7, 747.e1–747.e7.

Field, Andy, Jeremy Miles, and Zoe Field (2012). *Discovering statistics using R*. London: Sage Publications, pp. 1–957.

Fillingim, Roger B. (2017). "Individual differences in pain: Understanding the mosaic that makes pain personal." In: *Pain* 158.4(Suppl 1), S11–S18.

Fröhlich, Stefan, Loris Peterhans, Christoph Stern, Walter O Frey, Reto Sutter, and Jörg Spörri (2020). "Remarkably high prevalence of overuse-related knee complaints and MRI abnormalities in youth competitive alpine skiers: a descriptive investigation in 108 athletes aged 13–15 years." In: *BMJ Open Sport & Exercise Medicine* 6.1, e000738.

Gholami Borujeni, Behnam and Ali Yalfani (2019). "Reduction of postural sway in athletes with chronic low back pain through eight weeks of inspiratory muscle training: A randomized controlled trial." In: *Clinical Biomechanics* 69, pp. 215–220.

HOCOMA AG (2018). *User Manual English We move you*.

Harris, Paul A, Robert Taylor, Robert Thielke, Jonathon Payne, Nathaniel Gonzalez, and Jose G Conde (2009). "Research electronic data capture (REDCap)-A metadata-driven methodology and workflow process for providing translational research informatics support." In: *Journal of Biomedical Informatics* 42.2, pp. 377–381.

Hayden, Jill, Maurits W van Tulder, Antti Malmivaara, and Bart W Koes (2005). "Exercise therapy for treatment of non-specific low back pain." In: *Cochrane Database of Systematic Reviews* 3, CD000335.

Heneweer, Hans, Luc Vanhees, and H. Susan J. Picavet (2009). "Physical activity and low back pain: A U-shaped relation?" In: *Pain* 143.1-2, pp. 21–25.

Hildebrandt, Carolin, Renate Oberhoffer, Christian Raschner, Erich Müller, Christian Fink, and Lisa Steidl-Müller (2021). "Training load characteristics and injury and illness risk identification in elite youth ski racing: A prospective study." In: *Journal of Sport and Health Science* 10.2, pp. 230–236.

Hlaing, Su Su, Rungthip Puntumetakul, Sawitri Wanpen, and Rose Boucaut (2020). "Balance control in patients with subacute non-specific low back pain, with and without lumbar instability: A cross-sectional study." In: *Journal of Pain Research* 13, pp. 795–803.

Hoffmann, Tammy C., Paul P. Glasziou, Isabelle Boutron, Ruairidh Milne, Rafael Perera, David Moher, Douglas G. Altman, Virginia Barbour, Helen Macdonald, Marie Johnston, Sarah E.Lamb Kadoorie, Mary Dixon-Woods, Peter McCulloch, Jeremy C. Wyatt, An Wen Chan Phelan, and Susan Michie (2014). "Better reporting of interventions: Template for intervention description and replication (TIDieR) checklist and guide." In: *BMJ* 348, g1687.

Hügli, Anna Sabrina, Markus Josef Ernst, Jan Kool, Fabian Marcel Rast, Anne-Kathrin Rausch-Osthoff, Angelika Mannig, Sarah Oetiker, and Christoph Michael Bauer (2015). "Adherence to home exercises in non-specific low back pain. A randomised controlled pilot trial." In: *Journal of Bodywork and Movement Therapies* 19.1, pp. 177–185.

Jacobs, Jesse V., Carrie L. Roy, Juvena R. Hitt, Roman E. Popov, and Sharon M. Henry (2016). "Neural mechanisms and functional correlates of altered postural responses to perturbed standing balance with chronic low back pain." In: *Neuroscience* 339, pp. 511–524.

Jansen-Kosterink, Stephanie M., Rianne M.H.A. Huis In 'T Veld, Christian Schönauer, Hannes Kaufmann, Hermie J. Hermens, and Miriam M.R. Vollenbroek-Hutten (2013). "A Serious Exergame for Patients Suffering from Chronic Musculoskeletal Back and Neck Pain: A Pilot Study." In: *Games for Health Journal* 2.5, pp. 299–307.

Jones, Christopher M., Peter C. Griffiths, and Stephen D. Mellalieu (2017). "Training Load and Fatigue Marker Associations with Injury and Illness: A Systematic Review of Longitudinal Studies." In: *Sports Medicine* 47, pp. 943–974.

Kahraman, Buse Ozcan, Turhan Kahraman, Orhan Kalemci, and Yesim Salik Sengul (2018). "Gender differences in postural control in people with nonspecific chronic low back pain." In: *Gait & Posture* 64, pp. 147–151.

Karayannis, Nicholas V., Rob J.E.M. E M Smeets, Wolbert van den Hoorn, and Paul W. Hodges (2013). "Fear of Movement Is Related to Trunk Stiffness in Low Back Pain." In: *PLoS ONE* 8.6, e67779.

Kassambara, Alboukadel (2021). *rstatix: Pipe-Friendly Framework for Basic Statistical Tests*. R package version 0.7.0.

Kent, Peter, Robert Laird, and Terry Haines (2015). "The effect of changing movement and posture using motion-sensor biofeedback, versus guidelines-based care, on the clinical outcomes of people with sub-acute or chronic low back pain-a multicentre, cluster-randomised, placebo-controlled, pilot trial." In: *BMC Musculoskeletal Disorders* 16.131.

Kiers, Henri, Jaap H. van Dieën, Simon Brumagne, and Luc Vanhees (2015). "Postural sway and integration of proprioceptive signals in subjects with LBP." In: *Human Movement Science* 39, pp. 109–120.

Kim, Seong Sik, Won Kyu Min, Jung Hee Kim, and Byoung Hee Lee (2014). "The effects of VR-based Wii fit yoga on physical function in middle-aged female LBP patients." In: *Journal of Physical Therapy Science* 26.4, pp. 549–552.

Knechtle, Deborah, Stefan Schmid, Magdalena Suter, Fabienne Riner, Greta Moschini, Marco Senteler, Petra Schweinhardt, and Michael L. Meier (2021). "Fear-avoidance beliefs are associated with reduced lumbar spine flexion during object lifting in pain-free adults." In: *Pain* 162.6, pp. 1621–1631.

Kondo, Akiko, Hitoshi Doki, and Kiyoshi Hirose (2012). "An attempt of a new motion measurement method for alpine ski turns using inertial sensors." In: *Procedia Engineering* 34, pp. 421–426.

Laird, Robert A, Jayce Gilbert, Peter Kent, and Jennifer L Keating (2014). "Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis." In: *BMC musculoskeletal disorders* 15, 229.

Leeuw, Maaike, Mariëlle E.J.B. Goossens, Gerard J.P. van Breukelen, Katja Boersma, and Johan W.S. Vlaeyen (2007). "Measuring Perceived Harmfulness of Physical Activities in Patients With Chronic Low Back Pain: The Photograph Series of Daily Activities—Short Electronic Version." In: *The Journal of Pain* 8.11, pp. 840–849.

Lemeunier, Nadège, Charlotte Leboeuf-Yde, and Olivier Gagey (2012). "The natural course of low back pain: a systematic critical literature review." In: *Chiropractic and Manual Therapies 2012 20:1* 20.1, 33.

Lin, Ivan, Louise Wiles, Rob Waller, Roger Goucke, Yusuf Nagree, Michael Gibberd, Leon Straker, Chris G. Maher, and Peter P.B. O'Sullivan (2020). "What does best practice care for musculoskeletal pain look like? Eleven consistent recommendations from high-quality clinical practice guidelines: Systematic review." In: *British Journal of Sports Medicine* 54, pp. 79–86.

Lomond, Karen V., Sharon M. Henry, Juvena R. Hitt, Michael J. DeSarno, and Janice Y. Bunn (2014). "Altered postural responses persist following physical therapy of general versus specific trunk exercises in people with low back pain." In: *Manual Therapy* 19.5, pp. 425–432.

Low, Daniel C, Gregory S Walsh, and Marco Arkesteijn (2017). "Effectiveness of Exercise Interventions to Improve Postural Control in Older Adults: A Systematic Review and Meta-Analyses of Centre of Pressure Measurements." In: *Sports Med* 47.1, pp. 101–112.

Luque-Suarez, Alejandro, Javier Martinez-Calderon, and Deborah Falla (2019). "Role of kinesiophobia on pain, disability and quality of life in people suffering from chronic musculoskeletal pain: A systematic review." In: *British Journal of Sports Medicine* 53.9, pp. 554–559.

Macedo, Luciana Gazzi, Jane Latimer, Christopher G. Maher, Paul W. Hodges, James H. McAuley, Michael K. Nicholas, Lois Tonkin, Chris J. Stanton, Tasha R. Stanton, and Ryan Stafford (2012). "Effect of Motor Control Exercises Versus Graded Activity in Patients With Chronic Nonspecific Low Back Pain: A Randomized Controlled Trial." In: *Physical Therapy* 92.3, pp. 363–377.

Magnusson, Marianne L., Daniel H. Chow, Zoe Diamandopoulos, and Malcom H. Pope (2008). "Motor control learning in chronic low back pain." In: *Spine* 33.16, E532–E538.

Maher, Chris G, Jill A Hayden, Bruno T Saragiotto, Tie P Yamato, and Matthew K Bagg (2021). "Letter in response to: 'Which specific modes of exercise training are most effective for treating low back pain? Network meta-analysis' by Owen et al." In: *British Journal of Sports Medicine* 55.5, pp. 285–286.

Maher, Chris, Martin Underwood, and Rachelle Buchbinder (2017). "Non-specific low back pain." In: *The Lancet* 389.10070, pp. 736–747.

Mair, Patrick and Rand Wilcox (2020). "Robust statistical methods in R using the WRS2 package." In: *Behavior Research Methods* 52.2, pp. 464–488.

Matheve, Thomas, Simon Brumagne, Christophe Demoulin, and Annick Timmermans (2018a). "Sensor-based postural feedback is more effective than conventional feedback to improve lumbopelvic movement control in patients with chronic low back pain: A randomised controlled trial." In: *Journal of NeuroEngineering and Rehabilitation* 15.1, 85.

Matheve, Thomas, Simon Brumagne, and Annick A.A. Timmermans (2017). "The Effectiveness of Technology-Supported Exercise Therapy for Low Back Pain." In: *American Journal of Physical Medicine & Rehabilitation* 96.5, pp. 347–356.

Matheve, Thomas, Guido Claes, Enzo Olivieri, and Annick Timmermans (2018b). "Serious gaming to support exercise therapy for patients with chronic non-specific low back pain: A feasibility study." In: *Games for Health Journal* 7.4, pp. 262–270.

Matheve, Thomas, Liesbet De Baets, Katleen Bogaerts, and Annick Timmermans (2019). "Lumbar range of motion in chronic low back pain is predicted by task-specific, but not by general measures of pain-related fear." In: *European Journal of Pain* 23.6, pp. 1171–1184.

Matheve, Thomas, Liesbet De Baets, Fabian Rast, Christoph Bauer, and Annick Timmermans (2018c). "Within/between-session reliability and agreement of lumbopelvic kinematics in the sagittal plane during functional movement control tasks in healthy persons." In: *Musculoskeletal Science and Practice* 33, pp. 90–98.

Matsumura, Seiji, Ken Ohta, Shin Ichiroh Yamamoto, Yasuharu Koike, and Toshitaka Kimura (2021). "Comfortable and convenient turning skill assessment for alpine skiers using imu and plantar pressure distribution sensors." In: *Sensors* 21.3, 834.

Mazaheri, Masood, Pieter Coenen, Mohamad Parnianpour, Henri Kiers, and Jaap H. van Dieën (2013). "Low back pain and postural sway during quiet standing with and without sensory manipulation: A systematic review." In: *Gait & Posture* 37.1, pp. 12–22.

Mazaheri, Masood, Elham Heidari, Javid Mostamand, Hossein Negahban, and Jaap H. Van Dieen (2014). "Competing effects of pain and fear of pain on postural control in low back pain?" In: *Spine* 39.25, E1518–E1523.

McCaskey, Michael A., Brigitte Wirth, Corina Schuster-Amft, and Eling D. De Bruin (2018). "Postural sensorimotor training versus sham exercise in physiotherapy of patients with chronic non-specific low back pain: An exploratory randomised controlled trial." In: *PLoS ONE* 13.3, e0193358.

Meinke, Anita, Rick Peters, Ruud Knols, Walter Karlen, and Jaap Swanenburg (2021). "Exergaming Using Postural Feedback From Wearable Sensors and

Exercise Therapy to Improve Postural Balance in People With Nonspecific Low Back Pain: Protocol for a Factorial Pilot Randomized Controlled Trial." In: *JMIR Research Protocols* 10.8, e26982.

Middelkoop, Marienke van, Sidney M. Rubinstein, Arianne P. Verhagen, Raymond W. Ostelo, Bart W. Koes, and Maurits W. van Tulder (2010). "Exercise therapy for chronic nonspecific low-back pain." In: *Best Practice and Research: Clinical Rheumatology* 24.2, pp. 193–204.

Mok, Nicola W., Sandra G. Brauer, and Paul W. Hodges (2004). "Hip strategy for balance control in quiet standing is reduced in people with low back pain." In: *Spine(Phila Pa 1976)* 29.6, E107–12.

Nicolson, Philippa J.A., Rana S. Hinman, Tim V. Wrigley, Paul W. Stratford, and Kim L. Bennell (2018). "Self-reported home exercise adherence: A validity and reliability study using concealed accelerometers." In: *Journal of Orthopaedic and Sports Physical Therapy* 48.12, pp. 943–950.

Nieuwenhuis, Rense, Manfred te Grotenhuis, and Ben Pelzer (2012). "Influence.ME: Tools for detecting influential data in mixed effects models." In: *R Journal* 4, pp. 38–47.

Nordstoga, Anne Lovise, Ingebrigt Meisingset, Ottar Vasseljen, Tom I.L. Nilsen, and Monica Unsgaard-Tøndel (2019). "Longitudinal associations of kinematics and fear-avoidance beliefs with disability, work ability and pain intensity in persons with low back pain." In: *Musculoskeletal Science and Practice* 41, pp. 49–54.

Oliveira, Crystian B, Chris G Maher, Rafael Z Pinto, Adrian C Traeger, Chung-Wei Christine Lin, Jean-François Chenot, Maurits Van Tulder, and Bart W Koes (2018). "Clinical practice guidelines for the management of non-specific low back pain in primary care: an updated overview." In: *European Spine Journal* 27.11, pp. 2791–2803.

Osumi, Michihiro, Masahiko Sumitani, Yuko Otake, Tomohiko Nishigami, Akira Mibu, Yuki Nishi, Ryota Imai, Gosuke Sato, Yusuke Nagakura, and Shu Morioka (2019). "Kinesiophobia modulates lumbar movements in people with chronic low back pain: a kinematic analysis of lumbar bending and returning movement." In: *European Spine Journal* 28, pp. 1572–1578.

Øverås, Cecilie K., Morten Villumsen, Iben Axén, Miriam Cabrita, Charlotte Leboeuf-Yde, Jan Hartvigsen, and Paul J. Mork (2020). "Association between objectively measured physical behaviour and neck- and/or low back pain: A systematic review." In: *European Journal of Pain* 24.6, pp. 1007–1022.

Owen, Patrick J, Clint T Miller, Niamh L Mundell, Simone J J M Verswijveren, Scott D Tagliaferri, Helena Brisby, Steven J Bowe, and Daniel L Belavy (2020). "Which specific modes of exercise training are most effective for treating low back pain? Network meta-analysis." In: *British Journal of Sports Medicine* 54.21, pp. 1279–1287.

Park, Ji Hyuk, Sang Heon Lee, and Dae Sik Ko (2013). "The effects of the Nintendo Wii exercise program on chronic work-related low back pain in industrial workers." In: *Journal of Physical Therapy Science* 25.8, pp. 985–988.

Parreira, Patricia, Chris G. Maher, Daniel Steffens, Mark J. Hancock, and Manuela L. Ferreira (2018). "Risk factors for low back pain and sciatica: an umbrella review." In: *Spine Journal* 18.9, pp. 1715–1721.

Peterhans, Loris, Stefan Fröhlich, Christoph Stern, Walter O. Frey, Mazda Farshad, Reto Sutter, and Jörg Spörri (2020). "High Rates of Overuse-Related Structural Abnormalities in the Lumbar Spine of Youth Competitive Alpine Skiers: A Cross-sectional MRI Study in 108 Athletes:" in: *The Orthopaedic Journal of Sports Medicine* 8.5.

Pincus, Tamar, Rob J.E.M. Smeets, Maureen J. Simmonds, and Michael J.L. Sullivan (2010). "The fear avoidance model disentangled: Improving the clinical utility of the fear avoidance model." In: *Clinical Journal of Pain* 26.9, pp. 739–746.

Pistolesi, Francesco and Beatrice Lazzerini (2020). "Assessing the Risk of Low Back Pain and Injury via Inertial and Barometric Sensors." In: *IEEE Transactions on Industrial Informatics* 16.11, pp. 7199–7208.

Prieto, Thomas E., Joel B. Myklebust, Raymond G. Hoffmann, Eric G. Lovett, and Barbara M. Myklebust (1996). "Measures of postural steadiness: Differences between healthy young and elderly adults." In: *IEEE Transactions on Biomedical Engineering* 43.9, pp. 956–966.

R Core Team (2021). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria.

Rabbi, Mashfiqui, Min S.H. Aung, Geri Gay, M. Cary Reid, and Tanzeem Choudhury (2018). "Feasibility and acceptability of mobile phone-based auto-personalized physical activity recommendations for chronic pain self-management: Pilot study on adults.” In: *Journal of Medical Internet Research* 20.10, e10147.

Revelle, William (2021). *psych: Procedures for Psychological, Psychometric, and Personality Research*. Northwestern University. Evanston, Illinois.

Ribeiro, Daniel Cury, Stephan Milosavljevic, Jane Terry, and J. H. Abbott (2020). “Effectiveness of a lumbopelvic monitor and feedback device to change postural behaviour: The ELF cluster randomised controlled trial.” In: *Occupational and Environmental Medicine* 77.7, pp. 462–469.

Ribeiro, Daniel Cury, Gisela Sole, J. Haxby Abbott, and Stephan Milosavljevic (2014). “The effectiveness of a lumbopelvic monitor and feedback device to change postural behavior: A feasibility randomized controlled trial.” In: *Journal of Orthopaedic and Sports Physical Therapy* 44.9, pp. 702–711.

Roland, Martin and Richard Morris (1983). “A Study of the Natural History of Back Pain: Part I: Development of a Reliable and Sensitive Measure of Disability in Low-Back Pain.” In: *SPINE* 8.2, pp. 141–144.

Rönnby, Sara, Oscar Lundberg, Kristina Fagher, Jenny Jacobsson, Bo Tillander, Håkan Gauffin, Per Olof Hansson, Örjan Dahlström, and Toomas Timpka (2018). “mHealth self-report monitoring in competitive middle-and long-distance runners: Qualitative study of long-term use intentions using the technology acceptance model.” In: *JMIR mHealth and uHealth* 6.8, e10270.

Ruhe, Alexander, René Fejer, and Bruce Walker (2010). “The test–retest reliability of centre of pressure measures in bipedal static task conditions – A systematic review of the literature.” In: *Gait & Posture* 32.4, pp. 436–445.

Ruhe, Alexander, René Fejer, and Bruce Walker (2011). “Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: A systematic review of the literature.” In: *European Spine Journal* 20.3, pp. 358–368.

Rusu, Adina Carmen, Nina Kreddig, Dirk Hallner, Janina Hülsebusch, and Monika I Hasenbring (2014). “Fear of movement/(Re)injury in low back pain: confirmatory validation of a German version of the Tampa Scale for Kinesiophobia.” In: *BMC Musculoskeletal Disorders* 15, 280.

Sadler, Sean G., Martin J. Spink, Alan Ho, Xanne Janse De Jonge, and Vivienne H. Chuter (2017). “Restriction in lateral bending range of motion, lumbar lordosis, and hamstring flexibility predicts the development of low back pain: A systematic review of prospective cohort studies." In: *BMC Musculoskeletal Disorders* 18.1, 179.

Saraceni, Nic, Peter Kent, Leo Ng, Amity Campbell, Leon Straker, and Peter O'Sullivan (2020). "To flex or not to flex? Is there a relationship between lumbar spine flexion during lifting and low back pain? A systematic review with meta-analysis." In: *Journal of Orthopaedic and Sports Physical Therapy* 50.3, pp. 121–130.

Saragiotto, Bruno T., Christopher G. Maher, Tiê P. Yamato, Leonardo O.P. Costa, Luciola C. Menezes Costa, Raymond W.J.G. Ostelo, and Luciana G. Macedo (2016). "Motor control exercise for chronic non-specific low-back pain." In: *Cochrane Database of Systematic Reviews* 1, CD012004.

Sato, Takashi et al. (2021). "Effects of Nintendo Ring Fit Adventure Exergame on Pain and Psychological Factors in Patients with Chronic Low Back Pain." In: *Games for Health Journal* 10.3, pp. 158–164.

Schelldorfer, Sarah, Markus Josef Ernst, Fabian Marcel Rast, Christoph Michael Bauer, André Meichtry, and Jan Kool (2015). "Low back pain and postural control, effects of task difficulty on centre of pressure and spinal kinematics." In: *Gait & Posture* 41.1, pp. 112–118.

Schmidt, Richard A, Timothy Donald Lee, Carolee J Winsetein, Gabriele Wulf, and Howard N. Zelaznik (2019). "Augmented Feedback." In: *Motor control and learning : a behavioral emphasis*. 6th ed. Champaign IL: Human Kinetics. Chap. 11, pp. 341–373.

Schoeb, Thierry, Loris Peterhans, Stefan Fröhlich, Walter O. Frey, Christian Gerber, and Jörg Spörri (2020). "Health problems in youth competitive alpine skiing: A 12-month observation of 155 athletes around the growth spurt." In: *Scandinavian Journal of Medicine and Science in Sports* 30.9, pp. 1758–1768.

Shanbehzadeh, Sanaz, Mahyar Salavati, Saeed Talebian, Khosro Khademi-Kalantari, and Mahnaz Tavahomi (2018). "Attention demands of postural control in non-specific chronic low back pain subjects with low and high pain-related anxiety." In: *Experimental Brain Research* 236, pp. 1927–1938.

Shumway-Cook, Anne and Marjorie H Woollacott (2017). "Normal Postural Control." In: *Motor Control: Translating Research into Clinical Practice*. 5th ed. Philadelphia: Wolters Kluwer. Chap. 7, pp. 153–182.

Simpson, Lauren, Monish M. Maharaj, and Ralph J. Mobbs (2019). "The role of wearables in spinal posture analysis: A systematic review." In: *BMC Musculoskeletal Disorders* 20.1, 55.

Skevington, S. M., M. Lotfy, and K. A. O'connell (2004). "The World Health Organization's WHOQOL-BREF quality of life assessment: Psychometric properties and results of the international field trial a Report from the WHOQOL Group." In: *Quality of Life Research* 13.2, pp. 299–310.

Snow, Greg (2013). *blockrand: Randomization for block random clinical trials*.

Spörri, Jörg, Josef Kröll, Benedikt Fasel, Kamiar Aminian, and Erich Müller (2017). "The Use of Body Worn Sensors for Detecting the Vibrations Acting on the Lower Back in Alpine Ski Racing." In: *Frontiers in Physiology* 8, 522.

Spörri, Jörg, Josef Kröll, Christian Haid, Benedikt Fasel, and Erich Müller (2015). "Potential Mechanisms Leading to Overuse Injuries of the Back in Alpine Ski Racing: A Descriptive Biomechanical Study." In: *https://doi.org/10.1177/0363546515588178* 43.8, pp. 2042–2048.

Sung, Won, Mathew Abraham, Christopher Plastaras, and Sheri P Silfies (2015). "Trunk motor control deficits in acute and subacute low back pain are not associated with pain or fear of movement." In: *The Spine Journal* 15.8, pp. 1772–1782.

Supej, Matej and H-C Holmberg (2021). "Monitoring the Performance of Alpine Skiers with Inertial Motion Units: Practical and Methodological Considerations." In: *Journal of Science in Sport and Exercise 2021* 3, pp. 249–256.

Swain, Christopher T. V., Fumin Pan, Patrick J. Owen, Hendrik Schmidt, and Daniel L. Belavy (2020). "No consensus on causality of spine postures or physical exposure and low back pain: A systematic review of systematic reviews." In: *Journal of Biomechanics* 102, 109312.

Taborri, Juri, Justin Keogh, Anton Kos, Alessandro Santuz, Anton Umek, Caryn Urbanczyk, Eline van der Kruk, and Stefano Rossi (2020). "Sport biomechanics applications using inertial, force, and EMG sensors: A literature overview." In: *Applied Bionics and Biomechanics* 2020, 2041549.

Tack, Christopher (2021). "Virtual reality and chronic low back pain." In: *Disability and Rehabilitation: Assistive Technology* 16.6, pp. 637–645.

Tagliaferri, Scott D., Maia Angelova, Xiaohui Zhao, Patrick J. Owen, Clint T. Miller, Tim Wilkin, and Daniel L. Belavy (2020). "Artificial intelligence to improve back pain outcomes and lessons learnt from clinical classification approaches: three systematic reviews." In: *npj Digital Medicine* 3, 93.

Thomas, James S., Christopher R. France, Megan E. Applegate, Samuel T. Leitkam, and Stevan Walkowski (2016). "Feasibility and Safety of a Virtual Reality Dodgeball Intervention for Chronic Low Back Pain: A Randomized Clinical Trial." In: *Journal of Pain* 17.12, pp. 1302–1317.

Tong, Huong Ly, Juan C. Quiroz, A. Baki Kocaballi, Sandrine Chan Moi Fat, Kim Phuong Dao, Holly Gehringer, Clara K. Chow, and Liliana Laranjo (2021). "Personalized mobile technologies for lifestyle behavior change: A systematic review, meta-analysis, and meta-regression." In: *Preventive Medicine* 148, 106532.

Uralde-Villanueva, Ibai López-de, Daniel Muñoz-García, Alfonso Gil-Martínez, Joaquín Pardo-Montero, Rosa Muñoz-Plata, Santiago Angulo-Díaz-Parreño, Miguel Gómez-Martínez, and Roy La Touche (2016). "A Systematic Review and Meta-Analysis on the Effectiveness of Graded Activity and Graded Exposure for Chronic Nonspecific Low Back Pain." In: *Pain Medicine* 17.1, pp. 172–188.

Valenzuela, Trinidad, Yoshiro Okubo, Ashley Woodbury, Stephen R. Lord, and Kim Delbaere (2018). "Adherence to Technology-Based Exercise Programs in Older Adults: A Systematic Review." In: *Journal of Geriatric Physical Therapy* 41.1, pp. 49–61.

Van Dieën, Jaap H., Herta Flor, and Paul W. Hodges (2017). "Low-Back Pain Patients Learn to Adapt Motor Behavior With Adverse Secondary Consequences." In: *Exercise and Sport Sciences Reviews* 45.4, pp. 223–229.

Villa-Sánchez, Bernardo, Mehran Emadi Andani, Giulia Menegaldo, Michele Tinazzi, and Mirta Fiorio (2019). "Positive verbal suggestion optimizes postural control." In: *Scientific Reports* 9.1, 6408.

Vlaeyen, J. W.S. and G. Crombez (1999). "Fear of movement/(re)injury, avoidance and pain disability in chronic low back pain patients." In: *Manual Therapy* 4.4, pp. 187–195.

Warnes, Gregory R, Ben Bolker, Thomas Lumley, Randall C Johnson. Contributions from Randall C. Johnson are Copyright SAIC-Frederick, Inc. Funded by the Intramural Research Program, of the NIH, National Cancer Institute, and Center for Cancer Research under NCI Contract NO1-CO-12400. (2018). *gmodels: Various R Programming Tools for Model Fitting*.

Weng, Lin-Man, Yi-Li Zheng, Meng-Si Peng, Tian-Tian Chang, Bao Wu, and Xue-Qiang Wang (2020). "A Bibliometric Analysis of Nonspecific Low Back Pain Research." In: *Pain Research & Management* 2020, 5396734.

Wertli, Maria M., Eva Rasmussen-Barr, Sherri Weiser, Lucas M. Bachmann, and Florian Brunner (2014). "The role of fear avoidance beliefs as a prognostic factor for outcome in patients with nonspecific low back pain: A systematic review." In: *Spine Journal* 14.5, 816–836.e4.

Whoqol Group (1998). "Development of the World Health Organization WHOQOL-BREF Quality of Life Assessment." In: *Psychological Medicine* 28.3, pp. 551–558.

Wiesinger, Günther F., Martin Nuhr, Michael Quittan, Gerold Ebenbichler, Gabriele Wölfl, and Veronika Fialka-Moser (1999). "Cross-Cultural Adaptation of the Roland-Morris Questionnaire for German-Speaking Patients With Low Back Pain." In: *SPINE* 24.11, pp. 1099–1103.

Willigenburg, Nienke W., Idsart Kingma, Marco J.M. Hoozemans, and Jaap H. van Dieën (2013). "Precision control of trunk movement in low back pain patients." In: *Human Movement Science* 32.1, pp. 228–239.

Wilson, Fiona, Clare L Ardern, Jan Hartvigsen, Kathryn Dane, Katharina Trompeter, Larissa Trease, Anders Vinther, Conor Gissane, Sarah-Jane McDonnell, JP Caneiro, Craig Newlands, Kellie Wilkie, David Mockler, and Jane S Thornton (2021). "Prevalence and risk factors for back pain in sports: a systematic review with meta-analysis." In: *British Journal of Sports Medicine* 55.11, pp. 601–607.

Winter, DA (1995). "Human balance and posture control during standing and walking." In: *Gait & Posture* 3.4, pp. 193–214.

Woby, Steve R., Neil K Roach, Martin Urmston, and Paul J Watson (2005). "Psychometric properties of the TSK-11: A shortened version of the Tampa Scale for Kinesiophobia." In: *Pain* 117.1-2, pp. 137–144.

Wu, Aimin, Lyn March, Xuanqi Zheng, Jinfeng Huang, Xiangyang Wang, Jie Zhao, Fiona M. Blyth, Emma Smith, Rachelle Buchbinder, and Damian Hoy (2020). "Global low back pain prevalence and years lived with disability from 1990 to 2017: estimates from the Global Burden of Disease Study 2017." In: *Annals of Translational Medicine* 8.6, 299.

Zadro, Joshua R., Debra Shirley, Milena Simic, Seyed J. Mousavi, Dragana Ceprnja, Katherine Maka, Jennie Sung, and Paulo Ferreira (2019). "Video-Game-Based Exercises for Older People with Chronic Low Back Pain: A Randomized Controlledtable Trial (GAMEBACK)." In: *Physical Therapy* 99.1, pp. 14–27.

Zhang, Chanjuan, Zhou Zhang, Yuelong Li, Chenyang Feng, Haiqi Meng, Yang Gao, Wai Leung Ambrose Lo, and Chuhuai Wang (2020). "Pain catastrophizing is related to static postural control impairment in patients with nonspecific chronic low back pain: A cross-sectional study." In: *Pain Research and Management* 2020, 9629526.