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DOCTORAL DISSERTATION

Technology-supported exercise therapy for chronic nonspecific low back pain

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General Introduction

1 A brief introduction to low back pain

1.1 What is low back pain an why is it important?

Low back pain (LBP) is defined as pain between the lower costal margins and the buttock creases, which may be accompanied by pain or neurological symptoms in one or both legs.[1,2] Typically, LBP is further defined in terms of symptom duration, and is categorised as acute (less than 6 weeks), subacute (6 to 12 weeks) or chronic LBP (more than 12 weeks).[3,4] The traditional view is that acute LBP has a good prognosis with the majority of patients recovering within six weeks. However, 33-56% of patients with acute LBP report a pain flare-up within a year and 13-28% do not completely recover after a 1 year period.[5-7] As such, this traditional view might have been overly optimistic.[8]

The life time prevalence of LBP has been reported to be as high as 84%, whereas at any given moment, about 18% of the people worldwide are experiencing LBP.[9,10] Low back pain has been identified as the leading cause of years lived with disability worldwide and it is the single most important reason for sick leave and early retirement.[8,11,12] The Belgian Healthcare Knowledge Centre conservatively estimates the LBP-related costs in Belgium to be as high as 1.6 billion euros per year.[13] Given the high prevalence of LBP and its enormous socioeconomic burden on society, LBP deserves our full attention in order to improve the prevention and management of this important problem.

1.2 Chronic nonspecific low back pain

Low back pain can be caused by a myriad of underlying diseases, such as renal problems, spondyloarthropathy, vertebral compression fractures, malignant processes or endometriosis, to name just a few. In these cases, LBP is secondary to a clear underlying pathology and is defined as specific LBP.[8,14] However, in about 90% of patients with chronic low back pain (CLBP), no pathoanatomic cause of the pain can be identified. As such, these patients are diagnosed as having chronic nonspecific LBP (CNSLBP).[8] In the recently revised International Classification of Diseases (ICD-11), CNSLBP is therefore categorised as a primary chronic pain condition, meaning that the pain is not secondary to an underlying disease.[4]

The diagnosis of CNSLBP is primarily based on a thorough patient interview and clinical examination. In case of a suspected serious pathology, (spinal) imaging for diagnostic purposes is warranted, but otherwise it has very limited value and should not be routinely performed.[15] When specific causes of CLBP (including radicular involvement) can be ruled out, the diagnosis of chronic *nonspecific* LBP can be made.[16] This diagnosis, however, is very broad and covers a wide variety of clinical presentations. For example, some persons with CNSLBP continue to work, participate in leisure activities and enjoy their lives, while others are highly disabled, on sick leave and unable to take part in social activities. This shows that the large population of patients with CNSLBP cannot be seen as a homogeneous group. Therefore, we need to approach patients with CLBP from an individual and multidimensional perspective.[8,14,17,18]

1.3 Chronic nonspecific low back pain: a multidimensional problem

Back in 1977, Engel was the first to introduce the '*biopsychosocial model*' in medicine.[19] Ten years later, Waddell applied this model specifically to the management of LBP.[20] Nowadays it has been widely accepted that LBP is an individual experience, which can be influenced by many factors, including genetic, physical, emotional, cognitive, lifestyle, social and behavioural aspects.[14,17] Acknowledging the relative contribution of these different factors is essential, as they will guide the assessment and treatment of the individual patient.[17,18,21] Related to this point, it has been recommended to take into account the dominant pain mechanism underlying the patient's problem.[17,18,22] Three different types of pain have been described: nociceptive, nociplastic and neuropathic pain.[23,24] Before going into further detail about the different types of pain, I will first provide a more general background on pain.

1.3.1 What is pain?

Pain is typically described as an unpleasant sensory and emotional experience, which may or may not be accompanied by tissue damage.[24] When noxious stimuli are detected by receptors in the tissues of the body, an afferent signal will be sent towards the dorsal horn of the spinal cord. Here, this signal can be transferred to a second order neuron that conducts this signal to the thalamus in the brain. From the thalamus, various connections are made to a network of different cortical areas that are typically activated during pain processing.[25,26] Traditionally, the neural system was viewed as a passive relay, much like a bunch of electrical wires that only transfer information from one point to another. As such, pain was thought to be solely dependent on the amount of nociceptive input or tissue damage. Spurred by the seminal work of Melzack and Wall in 1965,[27] it became clear that afferent signals could be modulated in the dorsal horn of the spinal cord by descending neurons from the brain (Fig. 1).[25,26]

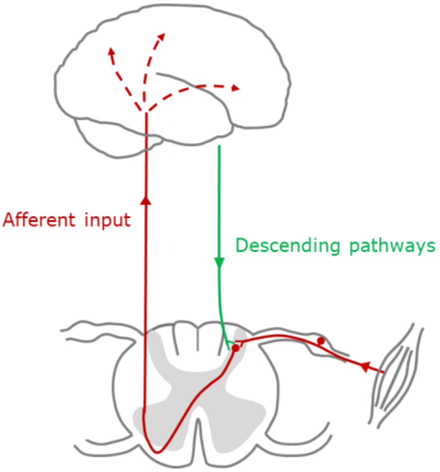

Fig. 1 Simplified representation of ascending and descending pain pathways

This modulation can result in either an inhibition or an amplification of the signal transmission in the synaps between the first and second order neuron. As such, a person will not always perceive the same peripheral stimulus in the same way.[25] Moreover, this implies that nociceptive input is neither sufficient, nor necessary to experience pain. A classic example to illustrate this is the role of expectations on pain. Depending on the expectations of a person, the same stimulus might be perceived as more or less painful.[28] This show that the experience of pain is not only dependent on the peripheral input, but also on the central processing of it. For some persons, pain is directly proportional to the afferent input (i.e. nociceptive pain), whereas for others this is clearly not the case (i.e. nociplastic pain).

1.3.2 Nociceptive pain - Peripherally mediated pain

Nociceptive pain arises from activation of nociceptors, and is described in terms of actual or threatened tissue damage (excluding neural tissue).[24] Nociceptive LBP is directly related to the response to mechanical loading of the spine. The pain will be clearly reproduced or eased by certain postures or movements, and is mainly driven by peripheral (nociceptive) afferent input.[17,18,29,30] As such, nociceptive pain is also referred to as '*peripherally mediated pain*'.[17,31] In patients with dominant peripherally mediated CLBP, physical factors play an important role as they can affect spinal loading. These physical factors can be intrinsic (i.e. related to person) or extrinsic (i.e. related to the environment).[32] Intrinsic factors can include movement patterns, movement variability, muscle control and strength, posture and spinal mobility. Extrinsic factors can include physical job demands (e.g. lifting heavy loads) or spinal loading during sports. For example, when a person has to handle heavy loads in awkward positions during his job, and does so by consistently using the same movement pattern, this could potentially lead to a suboptimal loading on the lumbar spine.[33] As a result, the person may develop LBP by peripheral nociceptive input from the local tissues.[32,33] For these types of patients, it is thought that interventions primarily targeting peripheral mechanisms, such as movement control, are indicated (also see paragraph 3.1).[17,18,34,35]

1.3.3 Nociplastic pain - Centrally mediated pain

When pain is due to altered nociception, but does not arise from actual or potential tissue damage, nor from a disease or damage of the neural system, it is termed nociplastic.[24] This infers that nociplastic pain is mainly driven by modulation in the central nervous system,[23] and is therefore sometimes referred to as '*centrally mediated pain'*.[17,31] The existence of central modulation is supported by studies showing altered cerebral activation, connectivity and structure in patients with chronic pain.[23] Altered central pain processing is thought to be the dominant underlying mechanism in about 25% of patients with CLBP.[36] The pain in this subgroup of patients is typically more intense and/or widespread, and its relation to mechanical loading is less clear.[22,36] The central processing of pain can be influenced by many factors, such as the context of the pain experience, the attention to pain-related information, cognitions and emotions.[26,37,38] Of particular importance for patients with CLBP are pain-catastrophising and pain-related fear, as these factors are highly prevalent and associated with higher levels of pain and disability in this population.[39-41] Evidence is emerging that pain-catastrophising and pain-related fear influence the central processing of pain,[37,38] and these factors have also been shown to increase to attention to pain and the difficulty to disengage from it, thereby facilitating pain perception.[42,43] For patients with dominant centrally mediated CLBP, these central mechanism should be primarily targeted during interventions (also see paragraph 3.2).[17,18,34,35]

1.3.4. Neuropathic pain

Neuropathic pain is caused by a lesion or a disease of the central or peripheral somatosensory nervous system.[24] Because neuropathic pain is secondary to a demonstrable lesion or disease, it is classified as a *specific cause* of LBP.[8] Given that this PhD project only focuses on patients with chronic *nonspecific* LBP, I will not further discuss neuropathic pain.

1.3.5 Mixed pain pattern

Many patients with CLBP present themselves with a combination of both peripherally and centrally mediated pain.[17,30,44] As such, both peripheral and central mechanisms should be taken into account when assessing and treating patients with CLBP. For example, an exercise therapy programme can be combined with pain neurophysiology education that addresses potential maladaptive beliefs about pain (e.g. pain equals damage).[45] Attention should also be paid to the potential relationship between both mechanisms. For example, we have shown that in patients with CLBP, a higher fear for lifting a box (~central mechanism) predicted a reduced lumbar range of motion during a lifting task (~peripheral mechanism).[46] This shows that categorising people into subgroups of purely centrally or peripherally mediated CLBP is too simplistic, but acknowledging that there is a spectrum of pain characteristics helps to understand the multidimensional nature of CLBP (Fig. 2).[17]

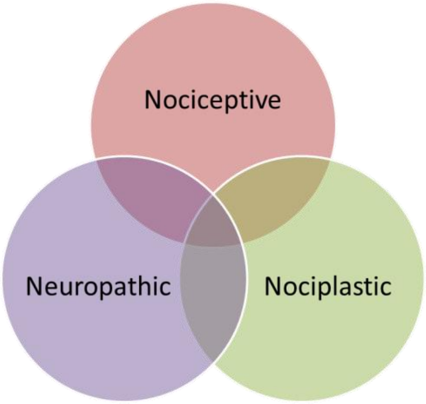

Fig. 2 Three different types of pain. While a certain type of pain can be dominant, individuals often present themselves with a combination of different types of pain.

2 Exercise therapy for chronic low back pain

2.1 Effectiveness of exercise therapy for CLBP

Exercise therapy is one of the most commonly used interventions for CLBP and is recommended in most clinical guidelines.[15] Systematic reviews have consistently shown that exercise therapy is effective for reducing pain and disability in patients with CLBP.[47-51] Despite these well-established positive results, effect sizes are only small to moderate and not all patients respond well to exercise therapy. A second observation from most systematic reviews is that no form of exercise therapy is superior to another.[47,51] For some researchers, this has led to the conclusion that it might not matter what form of exercise is provided, and therefore they suggest that the choice of exercises should depend on patient and therapist preferences, healthcare costs and safety.[47,52] However, this view is challenged by others (including myself), who argue that the choice of exercises should also be based on the clinical presentation of the individual patient, as this is expected to increase the effectiveness of exercise therapy.[17,18,35] Although some studies do not support this claim,[53] there is evidence in favour of an individual approach that takes into account the underlying mechanisms that are thought to be responsible for the patient’s problem (see paragraph 1.3). I will summarise a few important studies here.

A recent meta-analysis showed that movement control exercises were slightly more effective in the short term than other interventions to reduce pain and disability in patients with CNSLBP (effect size range= 0.33 to 0.38). However, when only studies were analysed that specifically included patients with movement control impairments, the effects were clearly larger (effect size range= 0.66 to 0.82).[48] In their randomised controlled trial, Macedo et al. compared motor control exercises to a graded activity intervention.[54] In a secondary analysis of the results, it became clear that patients with a clinical presentation of dominant peripherally mediated pain responded significantly better to the motor control exercises (targeting peripheral mechanisms), whereas graded activity (targeting central mechanisms) was more effective for patients without these symptoms.[35,54] These observations are further supported by a series of studies in neck pain.[35,55] A specific exercise programme for improving cervical and scapulothoracic muscle control resulted in 47% improvement in neck pain intensity in patients with mild to moderate idiopathic neck pain (suggestive for dominant nociceptive pain[35]). The same programme only led to a decrease of 16% in neck pain intensity in patients with chronic whiplash associated disorders and chronic widespread hyperalgesia (suggestive for dominant centrally mediated pain).[35]

The abovementioned studies support the idea that the choice of exercises should also be based on the presumed underlying mechanism of the LBP. Unfortunately, the majority of studies investigating exercise therapy for CLBP have not used this tailored approach,[56,57] which may explain why exercise therapy typically results in only small to moderate effects.[18,35,48]

2.2 Improving the effectiveness of exercise therapy

As described above, providing a tailored approach can be an important pathway for enhancing the treatment results of exercise therapy. Another approach is to support important treatment aspects of, and to remove the barriers to a (home-based) exercise programme. Often, removing barriers can help to support essential aspects of a successful intervention. For example, a lack of motivation is a frequently stated reason not to exercise, leading to an inadequate treatment adherence.[58,59] Nevertheless, a good adherence to exercise prescription is predictive for a better treatment outcome in patients with CLBP.[60,61] By removing a barrier (i.e. improving the motivation to exercise), an essential aspect of a successful intervention is supported (i.e. the adherence). How technology can remove barriers to, or support important aspects of exercise therapy is discussed in the next chapter.

3 Rationale for technology-supported exercise therapy

Given the small to moderate effects of ‘conventional’ exercise therapy for patients with CLBP, new approaches are warranted to improve treatment results. A potential avenue to obtain this is by using technological systems to support exercises, as technology may have the potential to remove barriers or to support aspects deemed important for treatment success after exercise therapy. I will focus on two main topics that are part of this PhD project: the use of technology for providing external postural feedback (see paragraph 3.1) and virtual reality (VR) distraction from pain (see paragraph 3.2).

3.1 External postural feedback – targeting peripheral mechanisms

3.1.1 Background and rationale

Most of the technological systems that are used during exercise therapy provide patients with external feedback (i.e. feedback coming from a source external to the person performing the task).[57,62,63] External feedback is essential for motor learning and to ensure a correct exercise performance.[64] These aspects are paramount during motor and movement control exercises. For example, patients can be asked to selectively activate specific spinal muscles (e.g. lumbar multifidus muscle),[34] to change movement patterns (e.g. reduce or increase movement at the lumbar spine)[33] or to dissociate between different body parts (e.g. thoracolumbar dissociation).[65] A first requisite for providing proper feedback on the quality of the performance is the ability to accurately assess this aspect. The problem is that, in absence of a therapist, patients typically have to rely on feedback from a mirror or palpation.[34] Especially in untrained assessors (i.e. patients), the accuracy of these types of feedback can be questioned,[66,67] which may lead to a suboptimal learning process.[64] Since technological systems can provide more accurate feedback on the quality of exercise performance (e.g. via movement sensors),[68] it is plausible that technological support may enhance the learning process.

3.1.2 What is known about postural feedback by technological systems?

An extensive overview of randomised controlled trials investigating the effects of technology-supported postural feedback on pain, disability and quality of life is given in **Chapter I** of this dissertation (**see Systematic Review**). Here, I will only focus on studies (including non RCTs) that assessed postural or movement-related parameters that were targeted by the technology-supported postural feedback.

Hügli et al.[69] conducted a randomised controlled pilot trial in patients with LBP > 4 weeks and an underlying movement control impairment. Both the control and intervention group received analytical movement control exercises during 9 physical therapy sessions, but the intervention group was also provided with postural feedback at home via inertial sensors. At the end of the treatment, the improvement in movement control, measured with a set of clinical movement control tests, was similar in both groups. In an attempt to reduce flexion-related postures and movements, Ribeiro et al.[70] conducted a randomised controlled pilot trial to investigate the effects of a wearable posture-monitor that provided feedback on flexion movements during daily life. Participants in the intervention group received an auditory signal when they exceeded a pre-specified cumulative postural threshold, which was based on the number of repetitions and the amount of time spent in a flexion position. Participants in the intervention group that were provided with constant feedback significantly reduced the number of spinal flexion movements/postures after a 4-week intervention period. Despite a medium to large effect of the feedback (Cohen's d= 0.6), the postural change was not significantly different to that of a control group receiving no feedback. Potentially, this was due to the small sample size of the study.[70] O'Sullivan et al.[71] investigated whether patients with CLBP who developed pain during a prolonged sitting task experienced less pain during the same task a week later when they were provided with real-time postural feedback from a system using a strain-gauge. During this second session, participants received vibrotactile feedback when they moved too far into an end-range position (either lumbar flexion or extension), urging them to change their posture. Under the feedback condition, participants spent significantly less time in their end-range lumbar position, which was associated with a reduction in pain.

3.1.3 Important research gaps

First, movement control exercises have a high potential to reduce pain and disability in patients with CLBP and an underlying movement control impairment.[48] Therefore, investigating which type of feedback is most effective to enhance the process of movement skill training is warranted. Up till now, no study has directly compared the effectiveness of technology-supported postural feedback with conventional postural feedback to improve movement control in patients with CLBP. Second, home exercises are an essential aspect in the treatment of patients with CLBP.[60,61] To enhance the additional benefit of technology-supported postural feedback, it should be feasible to provide this type of feedback during home exercises. In their pilot trial, Hügli et al. only used analytical movement control exercises (e.g. in 4-point kneeling) in a sample of patients with predominantly (sub)acute LBP.[69] Therefore, it remains unknown whether sensor-based postural feedback can be integrated in a home exercise programme containing tailored and functional movement control exercises for patients with CLBP. The functional aspect of the exercises is important as this is expected to enhance the transfer of the acquired movement skills from the practised situation to daily life activities.[72]

3.2 Attentional distraction – targeting central mechanisms

3.2.1 Background and rationale

Patients with CLBP often report a transient increase of pain during or after exercises, which is an important reason for them to stop exercising.[59,73] Since pain is an unpleasant experience, some patients are simply not willing to endure this temporary increase of pain.[74] Further, a widely held belief among patients with CLBP is that pain is a sign of tissue damage.[74] As a consequence, these patients may prevent or cease doing their exercises as they are convinced the exercises are harmful for their lumbar spine.[74,75] Other patients do not share this belief of harmfulness, but report that engaging in painful activities can lead to increased (emotional) suffering that will interfere with their daily functioning.[74] For example, a pain flare-up may prevent people to take part in social activities, which in turn can lead to frustration or a guilty feeling towards their spouse. Given these negative effects, it is worthwhile to explore effective means to reduce the pain during exercise therapy. A potential pathway via which technology may achieve this goal is by having patients perform their exercises with VR games. The chief mechanism behind this VR induced analgesia is thought to be attentional distraction.[76] During attentional distraction, the attention is shifted away from the pain towards a competing stimulus, thereby resulting in a pain decrease.[77] Various theories have been suggested to explain the analgesic effects of distraction, which are briefly outlined below (see Van Ryckeghem and Crombez for an extensive overview).[78]

The first theoretical frameworks were based on the concept of limited capacity and resources for information processing. The *limited capacity and resource theory*[79] states that when a person experiences pain and has to participate in a competing cognitive task (i.e. solving a puzzle), part of the attention needs to be directed towards this task. As such, less attentional resources will be available to process the pain, which will result in an analgesic effect.[79,80] Extending this model, Wickens introduced the *multiple resource theory*.[81] In short, this theory postulates that when a higher similarity between two information processing activities is present, the interference between the two tasks will increase. Accordingly, distraction by a somatosensory discrimination task (e.g. with heat stimuli) would lead to a larger analgesic effect than an auditory discrimination task.[82] The available research, however, does not fully support the abovementioned theories.[78,82] Therefore, the subsequent theoretical models took on a much broader perspective, and described that the attention to pain depends on the characteristics of the pain (bottom-up mechanism) and of the goals that are pursued by an individual (top-down mechanism).[83-85] Goal pursuit is a central aspect of the contemporary *motivational perspective on the attention to pain*.[78,85,86] Depending on a patient's goal prioritisation, pain may capture attention in two ways. When the goal is pain-related, attention will shift towards pain-related information, while the processing of information that is irrelevant for the pain will be inhibited.[85] A typical pain-related goal is to reduce the pain. For example, when a person develops LBP while attending a boring course, he/she will think of ways to reduce the pain and will probably pay less attention to what is told by the teacher. In contrast, a person might prioritise to pursue a goal that is not pain-related. Whether pain interrupts this ongoing activity or behaviour is dependent on the characteristics of the pain and the pursued goal. Referring to the former, the interruptive effect of pain will be larger when the pain is novel, more intense or perceived as threatening.[84,87] On the other hand, when it is highly important for a person to continue with an ongoing task (e.g. writing a PhD thesis) and to achieve the pursued goal (e.g. finishing it), the attentional interruption by pain will be less pronounced.

Based on this motivational perspective on pain, virtual reality games may prove to be a promising tool for obtaining an analgesic effect, because they are typically considered to be motivating and fun. In this way, they might be able to engage patients with the games, increasing the willingness to continue playing them. In other words, playing the VR games might be prioritised over pain control, thereby reducing the attention to pain. In addition, the positive emotions triggered by virtual reality games, such as fun and excitement,[88] can have a further positive effect on the pain.[26,85]

3.2.2 What is known about distraction induced analgesia?

Distraction induced analgesia has mainly been investigated during experimentally induced pain in healthy persons and during acute procedural pain (e.g. needle pain). The overall evidence shows that both VR and non-VR distraction are effective means for reducing pain under these conditions.[89-92] However, a recent meta-analysis showed that distraction did not have an analgesic effect in patients with chronic pain.[93] Of importance, none of the included studies used VR as a distraction. Indeed, the analgesic effects of VR distraction in patients with chronic pain has predominantly been investigated in small and uncontrolled studies.[94-101] In general, these studies indicate that VR distraction has an analgesic effect while patients are being immersed in a VR environment. However, the analgesic effects are highly variable and some patients do not experience a reduction in pain.[102] It has been hypothesised that this may be due to the fact that some patients with chronic pain have an attentional bias to pain.[93,103] This selective attention to pain and the difficulty to disengage from it can be driven by pain-related cognitions and emotions, such as pain catastrophising and pain-related fear.[42,43,104] However, the evidence that these factors attenuate distraction induced analgesia in patients with chronic pain is equivocal,[105-108] and has never been investigated in studies using VR as a means of distraction.

3.2.3 Important research gaps

Up till now, no RCT has investigated the analgesic effects of VR distraction in patients with chronic pain, including CLBP. As such, it remains unknown whether VR distraction is effective in reducing pain when compared to a control condition. Moreover, this also implies that there is a lack of knowledge regarding the potential moderating effects of pain-related cognitions and emotions on the analgesic effects of VR distraction. From a clinical point of view, the latter is important as it would enable us to better target this type of intervention to the patients most likely to respond to it.

4 Objectives and outline of the PhD thesis

4.1 Overall scope

The overall scope of this PhD project was to expand our knowledge on how technology can be used to remove barriers to, or to support important aspects of exercise therapy for patients with chronic nonspecific low back pain. We focused on three main aspects:

1. Integrating technological support into a tailored home exercise programme (Chapter I).
2. Peripheral mechanisms: providing postural feedback to improve lumbopelvic movement control (Chapter II).
3. Central mechanisms: attentional distraction with virtual reality games for reducing pain (Chapter III).

4.2 Outline of the PhD thesis

Chapter I consists of a systematic review and a feasibility study (Fig. 3). We first describe the **systematic review (Study 1)**, in which we investigated the current evidence for technology-supported exercise therapy for LBP. In addition, the type and the content of the technology-supported exercise therapy programmes were assessed. Subsequently, we present a **feasibility study (Study 2)** in which we investigated whether it was possible to integrate technological support into an exercise programme compliant with recommendations for exercise therapy.

Chapter II focuses on **peripheral mechanisms**. First, we describe a **reliability study (Study 3)** to establish the reliability and agreement of kinematic measurements during functional movement control tasks of the lumbar spine. Next, we present an **intervention study (Study 4)** during which we investigated whether sensor-based postural feedback was effective for **improving lumbopelvic movement control** in patients with CLBP. The choice of movement control tasks in the intervention study was based on the results of our reliability study.

Chapter III focuses on **central mechanisms**. We describe an **intervention study (Study 5)** to investigate the analgesic effects of **virtual reality distraction** during exercises in patients with CLBP. In addition, we assessed whether the analgesic effects were moderated by pain intensity, catastrophizing or pain-related fear.

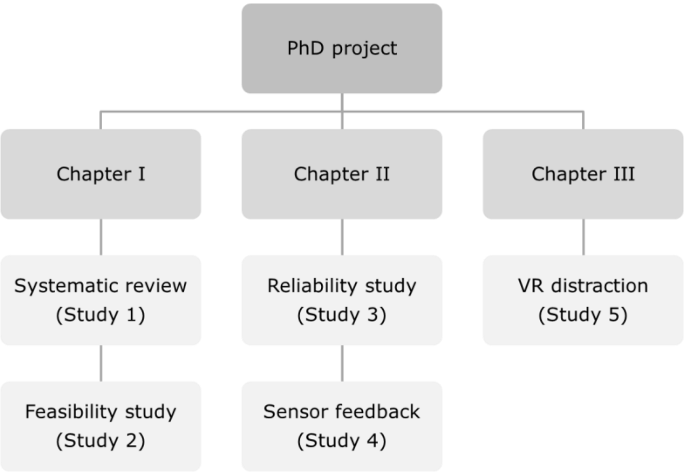

Fig 3 Outline of the PhD thesis

4.3 Specific objectives and research questions (RQs)

Objective 1: To review the available evidence on technology-supported exercise therapy (TSET) for patients with LBP (Study 1).

- RQ 1: Which technological systems have been used to support exercise therapy in patients with LBP?
- RQ 2: What is the content of the TSET-programmes?
- RQ 3: What is the effectiveness of TSET to improve pain, disability and quality of life in comparison to other interventions, a placebo intervention or no treatment?

Objective 2: To assess the feasibility of providing technology-supported postural feedback during tailored and functional movement control exercises at home (Study 2).

- RQ 1: Do patients find this intervention credible and do they expect it to result in improvement?
- RQ 2: Do patients remain motivated during a long-term intervention?
- RQ 3: Is it feasible to provide technological support at home?
- RQ 4: Are there any adverse events?

- RQ 5: What is the clinical effectiveness of this exercise programme?

Objective 3: To investigate the reliability and agreement of sagittal plane lumbopelvic kinematics during functional movement control tasks (Study 3). This study was conducted in preparation of study 4.

- RQ 1: What is the within and between session reliability of lumbopelvic kinematics during four functional movement control tasks in the sagittal plane?
- RQ2: What is the agreement and the minimal detectable change of the lumbopelvic kinematics between two sessions?

Objective 4: To compare the effectiveness of sensor-based postural feedback to conventional feedback to improve lumbopelvic movement control in patients with CLBP (Study 4).

- RQ 1: What is the effectiveness of sensor-based postural feedback to improve lumbopelvic movement control in patients with CNSLBP, when compared to feedback from a mirror or no feedback?
- RQ 2: Is there a transfer of the acquired movement skills from the practised task to an unpractised task?
- RQ 3: Do patients with CLNSLBP become dependent on the postural feedback?
- RQ 4: Are patients with CNSLBP equally capable of improving lumbopelvic movement control compared to healthy participants?

Objective 5: To investigate the analgesic effects of virtual reality distraction during exercises in patients with CNSLBP (Study 5).

- RQ 1: Does virtual reality distraction have an analgesic effect during and after exercises, when compared to a control group without distraction?
- RQ 2: Does virtual reality distraction reduce the time spent thinking during exercises, when compared to a control group without distraction?
- RQ 3: Do baseline levels of pain intensity, pain-related fear or pain catastrophising moderate the effects of virtual reality distraction?

Table 1 Overview of the studies

Chapter	Study		Main research questions	Participants	
	N°	Type		N	Main inclusion/exclusion criteria
I	1	Systematic Review	- Effectiveness of TSET? - Inventory TSET programmes	-	- RCTs - Technological support during exercises - Pain, disability or quality of life as outcome.
	2	Feasibility – Interventional	- Is a tailored, functional and home based TSET programme feasible?	10 CLBP	- CNSLBP - Underlying MC problem - No experience with TSET
II	3	Reliability	- Reliability and agreement of functional MC tasks?	20 H	- No MC exercises in past year - No LBP in the past year
	4	Interventional	- Is sensor FB more effective than FB from a mirror or no FB to improve lumbopelvic MC in CLBP? - Are patients with CLBP equally Capable of improving lumbopelvic MC compared to Healthy persons?	54 H – 54 CLBP	CNSLBP + H - no MC exercises in past year
III	5	Interventional	- Does VR distraction induce analgesia during/after exercises in patients with CLBP? - Does VR distraction reduce the time spent thinking of pain during exercises in pts with CLBP? - Does baseline pain intensity, pain catastrophising and pain-related fear moderate the effects of VR distraction?	84 CLBP	- CNSLBP - Baseline pain score 3-8/10 on NPRS - familiar with pelvic tilts - No experience with VR rehab

All participants were between 18-65 years old. CNSLBP= Chronic nonspecific low back pain, FB= feedback H= Healthy persons, NPRS= Numeric Pain Rating scale, TSET= Technology-supported exercise therapy, VR= virtual reality.

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Chapter I

Study 1

The effectiveness of technology-supported exercise therapy for low back pain: a systematic review.

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Abstract

Various technological systems have been developed to assist exercise therapy for low back pain. The aim of this systematic review is to provide an overview and to assess the effectiveness of the available technology-supported exercise therapy (TSET) programmes for low back pain. The electronic databases Pubmed, Embase, Cochrane Central Register of Controlled Trials, PEDro, IEEE and ACM were searched until January 2016. Randomized controlled trials (RCTs) using electronic technological systems simultaneously with exercise therapy for patients with low back pain were included. Twenty-five RCTs met the inclusion criteria. Seventeen studies involved patients with chronic low back pain, and EMG-biofeedback was the most prevalent type of technological support. This review shows that TSET appears to improve pain, disability and quality of life for patients with low back pain, and that a standard treatment combined with an additional TSET-programme might be superior to a standard treatment alone. However, TSET seems not more effective compared to other interventions or a placebo intervention for improving these outcomes, which may partially be explained by the analytical approach of the current TSET-programmes. For most technologies, only a limited number of RCTs are available, making it difficult to draw firm conclusions about the effectiveness of individual technological systems.

1 Introduction

Despite numerous treatment options, low back pain (LBP) remains an important health related problem with a substantial impact on daily functioning. The life time prevalence of LBP is reported to be as high as 84%, whereas the estimated prevalence of chronic LBP (CLBP) is about 23%.[1] Furthermore, in the industrialized countries CLBP is a leading cause of work absenteeism resulting in high economic and healthcare costs.[2]

Because of demographic changes, the prevalence of LBP is likely to increase in the future,[3,4] which in turn will contribute to the growing pressure on the healthcare system. The latter begs for innovative approaches that support both patients and therapists in their effort to obtain and offer high quality rehabilitation. Up till now, exercise therapy is commonly used as the treatment of choice in the rehabilitation of LBP.[5] Despite the positive effects on pain and disability, not all patients benefit from this type of treatment and the effect sizes are only small to moderate.[6-8]

In the neurological field, rehabilitation technologies have been developed for two decades and have proven to yield improvement in patients with stroke.[9,10] Apart from the use of surface electromyography (sEMG) and real-time ultrasound imaging (RUSI), the interest in technologies that support exercise therapy for LBP has emerged only in recent years. Various systems are available that provide extrinsic feedback to enhance the accuracy of exercise performance. This seems logical as patients with LBP often show an impaired internal feedback system, which leads to spinal control problems.[11] Currently, the feedback provided by physical therapists is usually based on palpation or inspection, however, the reliability of these assessments can vary considerably.[12-14] Therefore, it is thought that providing more accurate feedback by using technology could improve treatment outcomes.[15,16] Technology also aims to increase treatment adherence, which has been shown to be a predictor of treatment success of exercise programmes for patients with CLBP.[17,18] This might be achieved by providing automated feedback messages based on objective information about the training frequency and intensity gathered by technological systems, as this has already been demonstrated for other health problems.[19,20] In addition, technological systems can offer a more stimulating setting for the patient to practise, such as virtual reality environments.[21]

Despite the recent development of electronic systems to support exercise therapy for LBP, a detailed overview of the effectiveness of the various technology-supported exercise therapy (TSET) programmes is currently lacking. Therefore, the aim of this systematic review is (1) to inventory the available electronic technological systems supporting exercise therapy for LBP that have been evaluated in randomized controlled trials, and (2) to assess the effectiveness of technology-supported exercise therapy (TSET) for LBP, compared to other forms of rehabilitation, placebo interventions or no treatment.

2 Materials and methods

2.1 Data sources and searches

This systematic review was conducted according to the PRISMA-guidelines. A systematic search was performed up until January 2016 in the Pubmed, PEDro, EMBASE, Cochrane central register of controlled trials (CENTRAL), IEEE and ACM databases. The following key-words (truncation indicated with an asterisk symbol) were combined in various ways to identify relevant articles: low back pain, (bio)feedback, internet, whole body vibration, electrical stimulation, ultrasonography (ultrasound), technology, robotics, telemedicine, virtual reality, smartphone, mobile app*, sensor(s), motor control, exercise therapy and stabilization exercise. A detailed search strategy can be found in Additional File 1.

After removal of duplicates, two reviewers (T.M. and A.T.) independently screened the titles and abstracts of the obtained articles for eligibility. The relevant studies were read in full length to make a decision about the inclusion. Authors of papers were contacted for more information if this was necessary. The references of included articles and retrieved systematic reviews were screened for additional papers.

2.2 Study selection

2.2.1 Study design

Randomized controlled trials (RCTs) written in English or Dutch were included.

2.2.2 Participants

Studies containing an adult population with (sub)acute or chronic LBP of musculoskeletal origin were included. LBP lasting less than six weeks was defined as acute LBP, between six and 12 weeks as subacute LBP and more than 12 weeks as CLBP.[22] Trials including healthy subjects or patients with pelvic girdle pain, and studies on post-operative rehabilitation were excluded. If patients were described as having back pain, and no specific sub-analysis was made for LBP, the article was excluded.

2.2.3 Outcomes

To be included, at least one of the following outcomes had to be reported: pain, disability or quality of life.

2.2.4 Interventions

Studies had to compare TSET to other interventions, a placebo intervention or no treatment. Any type of exercise therapy routinely used for the treatment of LBP was included, as long as it was supported by technology. This implies that the technology had to be used simultaneously with the exercise therapy. Because the development of current and future technologies mainly focusses on electronic systems (e.g. sensors), only studies using technological devices with an electronic component were included. Purely mechanical systems, such as traditional fitness equipment, were not the scope of this review. Combined therapies were allowed as long as the independent effects of TSET could be assessed.[22] This implies that if a standard therapy was combined with an additional TSET-intervention, the control group should have received the same standard intervention as the TSET-group. For example, a study that compared physical therapy and TSET with physical therapy and stabilization exercises could be included in the review. If the control group would have received manipulative therapy and stabilization exercises, this study could not be included.

2.2.5 Data extraction and synthesis

The data extraction was performed independently by two reviewers (T.M. and A.T.), using a standardized form. The extracted data included the number of subjects, age, gender, duration of symptoms, technology-supported intervention, control intervention, outcomes (pain, disability and quality of life), measurement times and follow-up times.

When possible, effect sizes (Hedges' g) were calculated for between group differences. For this calculation, the sample sizes, means and standard deviations from continuous data were extracted. If the required information could not be retrieved from the articles, authors were contacted to provide the missing data. Effect sizes (ES) were interpreted according to Cohen's classification[23]: an ES of 0.2 was interpreted as small, 0.5 as medium, 0.8 as large.

Results were described as post-intervention, short term (closest to three months follow-up), intermediate term (closest to six months follow-up) or long term (closest to one year follow-up).[22]

2.2.6 Risk of bias assessment

The risk of bias was assessed using the checklist from the Cochrane Back Research Group (CBRG), which consists out of 12 items.[22] Before evaluating the included articles, a risk of bias assessment try-out was conducted on similar articles. Positive scores were given on items that fulfilled the criteria, and negative scores if this was obviously not the case. If there was insufficient information, items were labelled unsure. Following the guidelines of the CBRG, a study was categorized as having a low risk of bias if it had six or more positive items and no major flaws. Otherwise the study was classified as having a high risk of bias. The assessment was done independently by two reviewers (T.M. and A.T.). If any disagreements persisted after discussion, a third reviewer would be contacted for consensus. No studies were excluded based on their risk of bias assessment.

3 Results

3.1 Systematic search

A sensitive search strategy was used and yielded 6195 records. After removal of duplicates and screening on title and abstract, 96 papers were withheld for full-text reading. Finally, 25 articles were included in this review. A flowchart of the selection process can be found in Figure 1.

3.2 Risk of bias

A high level of agreement was reached on the risk of bias assessment resulting in a kappa value of 86% (95% CI = 0.81, 0.91) across the items. Out of the 25 included studies, 12 papers had a low risk of bias. Despite being described as RCTs, only eight studies reported an adequate randomization process and a concealed allocation. Blinding of therapists and outcome assessors was adequate in only four papers, while blinding of participants was adequate in five papers. Details on the risk of bias assessment are presented in Table 1.

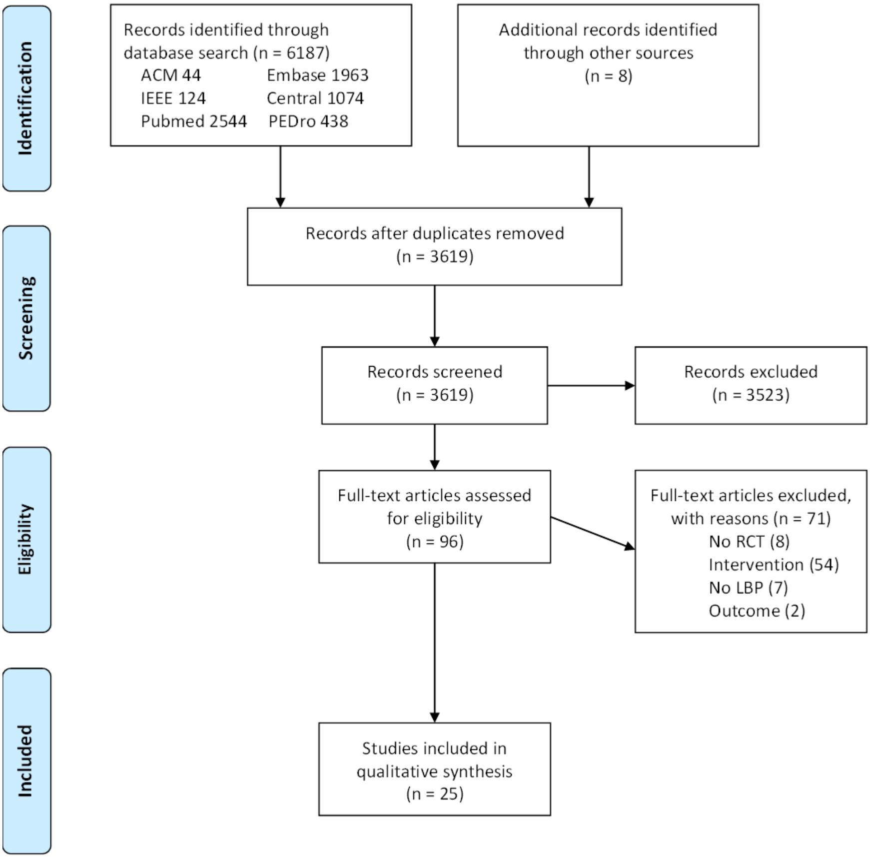

Fig 1 PRISMA flowchart

Table 1 Risk of bias of included studies

Author, year	Randomization adequate	Concealed allocation	Patient blinding	Therapist blinding	Outcome assessor blinded	Drop-out rate	Intention to treat	Selective outcome reporting	Baseline equal	Co-interventions	Compliance rates	Timing of outcome	Total
Ahmed, 2013 [24]	?	?	-	-	-	-	?	+	?	+	?	+	3
Asfour, 1990 [25]	?	?	-	-	?	?	?	+	+	+	?	+	4
Bush, 1985 [26]	?	?	+	-	-	-	-	+	+	?	?	+	4
de Sousa, 2009 [27]	?	?	+	-	-	+	?	+	+	?	+	+	6
del-Pozo Cruz, 2011 [28]	+	?	-	-	-	+	-	+	+	?	+	+	6
del-Pozo Cruz, 2012 [29]	+	+	-	+	-	+	+	+	+	?	+	+	9
del-Pozo Cruz, 2012 [30]	+	+	-	+	-	+	-	+	+	?	+	+	8
Donaldson, 1994 [31]	?	?	-	-	-	+	?	+	+	+	?	+	5
Hasenbring, 1999 [32]	-	-	-	-	-	-	-	+	+	-	?	+	3
Hides, 1996 [15]	+	+	-	-	-	+	-	+	+	?	+	+	7
Hügli, 2015 [33]	+	+	-	-	-	+	+	+	+	+	+	+	9
Kapitza, 2010 [34]	+	+	+	+	+	+	+	+	+	?	?	+	10
Kent, 2015 [35]	+	-	+	-	+	+	+	+	+	?	+	+	9
Kim, 2014 [36]	?	?	-	-	-	?	?	+	?	+	?	?	2
Krein, 2013 [37]	+	+	-	?	+	+	+	+	+	?	-	+	8
Magnusson, 2008 [38]	?	?	-	-	-	-	?	-	+	?	?	+	2
Massé-Alarie, 2013 [39]	?	?	+	+	+	?	?	+	+	?	+	+	7
Miller, 2004 [40]	+	+	-	-	-	-	?	+	?	?	?	+	4
Newton-John, 1995 [41]	-	-	-	-	-	-	-	+	+	?	?	+	3
Nouwen, 1983 [42]	?	?	+	-	-	+	+	+	-	?	+	+	6
Park, 2013 [43]	?	?	-	-	-	+	+	-	+	+	?	+	5
Rittweger, 2002 [44]	?	?	-	?	-	+	-	+	+	+	?	+	5
Stuckey, 1986 [45]	?	?	-	-	-	+	-	+	+	+	?	+	5
Unsgaard-Tøndel, 2010 [46]	+	+	-	-	-	+	+	+	+	?	+	+	8
Yang, 2015 [47]	?	?	-	-	-	+	+	+	+	?	?	+	5

+= criterion fulfilled, -= criterion not fulfilled, ?= unclear whether criterion is fulfilled.

3.3 Inventory and characteristics of TSET for LBP

Most of the studies (17/25) involved a CLBP population. Two studies used patients with acute LBP,[15,32] two studies from the same cohort used subjects with sub-acute LBP,[29,30] and four studies included patients with both (sub)acute and chronic LBP.[33,35,36,40] Ten different types of supportive technologies were described. EMG-Feedback (EMG-FB) was used in nine papers, while for the other technologies a maximum of three studies per technology was available. Table 2 provides an overview of the different TSET-programmes with comparisons. A detailed description of the study characteristics can be found in Additional File 2.

Table 2 Summary of TSET-programmes and their comparisons

TSET	Comparison
Surface EMG-feedback for increasing or decreasing paravertebral muscle activity (n= 6)	Waiting list (n= 3),[26,41,42] placebo (n= 2),[26,45] relaxation exercises (n= 2),[31,45] CBT (n= 2),[32,41] education (= 1),[31] usual care (n= 1)[32]
Surface EMG-feedback for strengthening or stabilization exercises (n= 3)	Standard physical therapy (n= 1),[25] exercises without feedback (n= 1),[24] waiting list (n= 1)[27]
RUSI for transversus abdominis muscle training (n= 1)	Sling exercises (n= 1),[46] general exercises[46]
RUSI for multifidus muscle training (n= 1)	Medical management (n= 1)[15]
Internet mediated exercise interventions (n= 3)	Exercises without online support (n= 1),[37] access to website containing ergonomic advice (n= 2)[29,30]
Nintendo Wii (n= 2)	Physical therapy and trunk stabilization exercises (n= 2),[36,43] physical therapy (n= 1)[43]
Whole-body vibration (n= 3)	Strengthening exercises (n= 1),[44] standard medical care (n= 1),[28] stabilization exercises (n= 1)[47]
Postural feedback (n= 3)	Back school (n= 1),[38] stabilization exercises (n= 1),[33] guideline-based physical therapy (n= 1)[35]
Respiratory feedback (n= 1)	Placebo respiratory feedback (n= 1)[34]
Peripheral magnetic stimulation (n= 1)	Sham stimulation (n= 1)[39]
Video instructions (n= 1)	Exercises without video instructions (n= 1)[40]

CBT= cognitive behavioural therapy; EMG= electromyography; RUSI= real-time ultrasound imaging; TSET= technology-supported exercise therapy.

3.4 Effectiveness of TSET

Pooling of data was considered inappropriate because of the substantial number of studies with a high risk of bias and because of clinical heterogeneity of the studies.[22] Therefore, no meta-analysis was performed, but effect sizes for individual studies are provided in Tables 3, 4 and 5. Positive effect sizes have to be interpreted in favour of the TSET-intervention, whereas negative effect sizes favor the comparison (i.e. other intervention, placebo or waiting list).

3.4.1 Acute LBP

One study compared a standard EMG-FB programme to individualized cognitive behavioural therapy (CBT), with both groups also receiving standard conservative care.[32] The EMG-FB group had significantly less improvement in pain post-treatment (ES= -0.86) and at intermediate term (ES= -0.40), but no differences were found for disability compared to the CBT-group.

One study showed that the addition of RUSI-supported multifidus muscle training to standard medical care did not result in a greater reduction in pain and disability post-treatment and at six weeks follow-up.[15] However, the TSET-group experienced significantly less LBP recurrences during a three year follow-up period.[48]

3.4.2 Sub-acute low back pain

Two studies from the same cohort of office workers assessed the effects of adding a web-based exercise programme to standard preventive occupational care.[29,30] Disability (ES= 1.61) and quality of life significantly improved after the intervention in the TSET-group, but not in the control group, and a significant between group difference was present.

3.4.3 Chronic low back pain

3.4.3.1 Standard treatment and TSET vs. standard treatment alone

Three out of four studies showed beneficial effects on pain when a TSET-programme was added to a standard treatment (ES range= 0.38, 0.75).[28,38,47] The two studies reporting quality of life[28,38] showed better results for the TSET-group (ES= 0.38) and mixed results were reported for disability in two studies

(ES range= 0.06, 0.27).[28,47] The positive effects were found in studies with an additional whole-body vibration intervention[28,47] or a motor learning programme with postural feedback.[38] Adding lumbar extensor strengthening exercises with EMG-FB to a two week physical therapy programme did not result in a greater reduction in pain.[25]

3.4.3.2 TSET vs. other interventions

Eight studies compared TSET to other interventions.[24,31,37,41,43-46] Technology-supported exercise therapy reduced pain significantly more than other interventions in two studies,[24,37] five studies found no differences,[31,37,41,44,46] and in one paper TSET was less effective.[45] Concerning disability, four studies showed no differences,[37,41,44,46] and in one paper TSET was less effective.[45] No differences in quality of life were found in one study.[37]

In four studies, patients were asked to increase or decrease muscle activity from the paravertebral extensors, while they were provided with EMG-FB from these muscles. No differences were found between EMG-FB and education[31] or CBT[41] for pain or disability. Compared to relaxation exercises, EMG-FB was less effective for reducing disability[45] and mixed results were shown for pain reduction.[31,45]

Trunk stabilization exercises with EMG-FB resulted in a significantly greater improvement in pain than trunk stabilization exercises without technological support (ES= 0.91).[24] In contrast, no differences in the reduction of pain and disability were found between whole-body vibration and strengthening exercises,[44] between transversus abdominis muscle training with RUSI and sling exercises or general strengthening,[46] and between an internet-mediated walking programme and a standard walking programme.[37] The latter study also reported no between group differences in quality of life.

In three studies, the technological support was the single difference between the experimental and control intervention.[24,37,45] In one paper the TSET intervention led to a greater reduction in pain,[24] one trial found no differences,[37] and TSET was less effective in another study.[45]

Table 3 Effect sizes of studies comparing a standard therapy and TSET to a standard therapy alone

Study	TSET	Comparison	Outcome	ES	*p*
Acute low back pain					
Hides et al., 1996 [15]	Standard medical care + multifidus muscle training with RUSI. TSET: 8 sessions, 2x/week.	Standard medical care	Pain (VAS)	-	NS
			Pain (MPQ)	-	NS
			Disability (RMQ)	-	NS
Sub-acute low back pain					
Del Pozo-Cruz et al., 2012[29,30]	Standard preventative occupational care + internet mediated exercises. TSET: 9-months of unsupervised daily exercises	Standard preventative occupational care	Disability (RMQ) [27]	1.61	< 0.01
			Disability (ODI) [28]	-	0.001
			QoL (EQ-5D-3L) [28]	-	< 0.001†
Chronic low back pain					
Asfour et al., 1990 [25]	Physical therapy + trunk extensor strengthening with EMG-FB. 2 weeks ST + 8 sessions TSET, 4x/week	Physical therapy. 2 weeks.	Pain (VAS)	0.34	NS
Del Pozo-Cruz et al., 2011 [28]	Standard medical care + WBV-training. TSET: 24 sessions, 2x/week.	Standard medical care	Pain (VAS)	0.76	0.006
			Disability (RMQ)	0.27	0.001
			Disability (ODI)	0.66	0.013
			QoL (EQ-5D-3L)	0.38	0.042
Magnusson et al., 2008 [38]	Standard rehabilitation + motor learning programme with postural FB. 5 sessions ST, 1x/week + 10 sessions of TSET, 2x/week.	Standard rehabilitation. 5 sessions, 1x/week.	Pain (VAS)	-	< 0.001
			Pain (VAS)*	-	< 0.05
			QoL (SF-36)	-	< 0.05†
			QoL (SF-36)*	-	< 0.05
Park et al., 2013 [43]	Physical therapy + Wii sports. 24 sessions, 3x/week	Physical therapy. 24 sessions, 3x/week	Pain (VAS)	-	NR
			QoL (RAND-36)	0.11	NR
				0.18	

Table 3 *Continued*

Study	TSET	Comparison	Outcome	ES	*p*
Yang et al., 2015 [47]	Stabilization exercises + WBV-exercises. 18 sessions, 3x/week.	Stabilization exercises. 18 sessions, 3x/week.	Pain (VAS) Disability (ODI)	0.75 0.06	< 0.05 NS
Mixed population					
Kent et al., 2015 [35]	Guideline-based physical therapy + motor control exercises with postural FB. 6-8 sessions over 10 weeks.	Guideline-based physical therapy. 6-8 sessions over 10 weeks.	Pain (QVAS) Disability (RMQ) Disability (PSFS)	1.27 1.74 1.87	< 0.05 < 0.05 < 0.05

All results are post-intervention, unless otherwise reported: *= intermediate term. Positive effect sizes are in favor of the TSET-group. When it was not possible to calculate an effect size, this is indicated with a hyphen (-). For *p*-values: All values are for between group comparisons, NS= non-significant, NR= not reported, ┼= for most of the sub-scales of the questionnaire. ADL= activities of daily life, EMG= electromyography, EQ-5D-3EL= European quality of life 5-dimensions-3-levels, ES= Hedges' g effect size, FB= feedback, MPQ= McGill pain questionnaire, ODI= Oswestry disability index, PSFS= Patient specific functioning scale, QoL= quality of life, QVAS= Quadruple visual analogue scale, RAND-36= RAND-36 health status inventory, RMQ= Roland Morris disability questionnaire, ST= standard therapy, TSET= technology-supported exercise therapy, VAS= visual analogue scale.

Table 4 Effect sizes of studies comparing TSET to other interventions

Study	TSET	Comparison	Outcome	ES	*p*
Acute Low back pain					
Hasenbring et al., 1999 [32]	Standard physiotherapy + PVM control exercises with EMG-FB. 12 sessions, 1x/week.	Standard physiotherapy + Cognitive behavioural therapy. 10-40 sessions (mean= 27).	Pain (VAS)	-0.86	$< 0.05^{\#}$
			Pain (VAS)*	-0.40	$< 0.05^{\#}$
			Disability (ADL-Q)	-0.30	NS
			Disability (ADL-Q)*	-0.20	NS
Chronic low back pain					
Ahmed et al., 2013 [24]	Stabilization exercises with EMG-FB. 12 sessions, 2x/week.	Stabilization exercises without EMG-FB. 12 sessions, 2x/week.	Pain (VAS)	0.89	0.027
Donaldson et al., 1994 [31]	PVM control exercises with EMG-FB. 10 sessions.	Relaxation exercises. 10 sessions.	Pain (VAS)	0.42	NS
			Pain (MPQ)	0.82	< 0.05
		Education. 10 sessions.	Pain (VAS)	0.68	NS
			Pain (MPQ)	0.78	NS
Krein et al., 2013 [37]	Walking programme with internet support. 12-month intervention.	Walking programme without internet support. 12-month intervention.	Pain (VAS)	0.09	NS
			Disability (RMQ)	0.29	NS
			QoL (SF-36)	-0.20	NS
Newton-John et al., 1995 [41]	Paravertebral muscle control exercises with EMG-FB. 8 sessions, 2x/week.	Cognitive behavioural therapy. 8 sessions, 2x/week.	Pain (NPRS)	0.20	NS
			Disability (PDI)	0.23	NS
			Disability (PDI)*	0.35	NS
Park et al., 2013 [43]	Physical therapy + Wii sports. 24 sessions, 3x/week.	Physical therapy + stabilization exercises. 24 sessions, 3x/week.	Pain (VAS)	-0.91	NR
			QoL (RAND-36)	-0.43	NR
Rittweger et al., 2002 [44]	Whole-body vibration. 18 sessions in 12 weeks.	Strengthening exercises. 18 sessions in 12 weeks.	Pain (VAS)	-0.11	NS
			Disability (PDI)	-0.09	NS
			Disability (PDI)*	-0.21	NS
Stuckey et al., 1986 [45]	PVM control exercises with EMG-FB. 8 sessions.	Relaxation exercises. 8 sessions.	Pain (VAS)	-0.2	$< 0.04^{\#}$
			Disability (ADL-Q)	-0.46	$< 0.03^{\#}$

Table 4 *Continued*

Study	TSET	Comparison	Outcome	ES	p
Unsgaard-Tøndel et al., 2010 [46]	TrA exercises with RUSI. 8 sessions, 1x/week.	Sling exercises. 8 sessions, 1x/week.	Pain (NPRS)	0.3	NS
			Disability (ODI)	0.36	NS
		General exercises. 8 sessions, 1x/week.	Pain (NPRS)	0.49	NS
			Disability (ODI)	0.56	NS
Mixed population					
Hügli et al., 2015 [33]	Motor control exercises with postural FB. 9 sessions.	Motor control exercises without postural FB. 9 sessions.	Disability (ODI)	-	NS
			Disability (PSFS)	-	NS
Kim et al., 2014 [36]	Wii fit yoga. 12 sessions, 3x/week.	Physical therapy and trunk stabilization. No info on number of treatments.	Pain (VAS)	1.47	< 0.01
			Disability (RMQ)	0.88	< 0.05
			Disability (ODI)	1.11	< 0.05
Miller et al., 2004 [40]	Exercises with video-instructions. ±4 sessions in 4-6 weeks.	Exercises with face-to-face instructions. ±4 sessions in 4-6 weeks.	Disability (RMQ)	0.18	NS
			QoL (SF-36)	-	NS┼

All results are post-intervention, unless otherwise reported: *= intermediate term. Positive effect sizes are in favor of the TSET-group. For *p*-values: All values are for between group comparisons, NS= non-significant, NR= not reported, #= significant in favor of the control group, ┼= for most subscales of the questionnaire. ADL-Q= activities of daily life questionnaire, EMG= electromyography, ES= Hedges' g effect size, FB= feedback, min.= minutes, MPQ= McGill pain questionnaire, NPRS= numeric pain rating scale, ODI= Oswestry disability index, PDI= pain disability index, PSFS= patient specific functioning scale, QoL= quality of life, PVM= paravertebral muscle, RAND-36= RAND-36 health status inventory, RMQ= Roland Morris disability questionnaire, SF-36= Short form-36, TrA= Transversus abdominis muscle, VAS= visual analogue scale.

3.4.2.3 TSET vs. placebo or waiting list

Six out of seven studies reporting pain as an outcome found no differences between TSET and a placebo[26,34,39,45] or a waiting list,[26,27,42] whereas four out of five studies showed no differences in disability.[27,34,39,45] In one study, the TSET-group improved significantly more on both outcomes.[41]

Four studies used paravertebral muscle control exercises with EMG-FB as technological support. EMG-FB exercises led to a greater reduction in pain and disability than a waiting list control group at post-treatment evaluation (ES range= 0.85, 1.19), but not at intermediate term in one study.[41] No significant between group differences in pain[26,42,45] or disability[45] were found in the other studies.

For both pain and disability, strengthening exercises with EMG-FB,[27] breathing exercises with respiratory FB,[34] and a single session of transversus abdominis muscle training with repetitive peripheral magnetic stimulation[39] were not more effective than a waiting list,[27] or a placebo (sham) intervention.[34,39]

3.4.4 Mixed population

Three studies compared TSET to another intervention and included patients with both (sub)acute and chronic LBP. A TSET-programme containing Wii-fit exercises led to greater reductions in pain and disability than physical therapy in one study (ES range= 0.88, 1.47).[36] Two studies comparing a conventional exercise programme with exercises supported by postural feedback[33] or video-instructions[40] showed no between group differences in disability[33,40] and most aspects of quality of life.[40] The addition of motor control exercises supported by postural feedback to guideline-based physical therapy led to greater improvements in pain (ES= 1.27) and disability (ES range= 1.74, 1.87) than guideline-based physical therapy alone.[35]

No differences in disability[33,40] and quality of life[40] were found in two studies where the technological support was the single difference between the interventions.

Table 5 Effect sizes of studies comparing TSET to placebo or a waiting list

Study	TSET	Comparison	Outcome	ES	*P*
Chronic low back pain					
Bush et al., 1985 [26]	PVM control exercises with EMG-FB. 8 sessions.	Placebo-FB. 8 sessions.	Pain (VAS)	-	NS
			Pain (VAS)*	-	NS
			Pain (MPQ)	-	NS
			Pain (MPQ)*	-	NS
		Waiting list	Pain (VAS)	-	NS
			Pain (VAS)*	-	NS
			Pain (MPQ)	-	NS
			Pain (MPQ)*	-	NS
De Sousa et al., 2009 [27]	Abdominal strengthening with EMG-FB. 16 sessions, 2x/week.	Waiting list	Pain (VAS)	0.53	NS
			Disability (RMQ)	0.47	NS
Kapitza et al., 2010 [34]	Breathing exercises with respiratory FB. 15 days of home exercises.	Breathing exercises with sham respiratory FB. 15 days of home exercises.	Pain (VAS)	-0.31	NS
			Disability (PDI)	0.03	NS
Massé-Alarie et al., 2013 [39]	TrA training with RPMS. One session.	TrA training with sham RPMS. One session.	Pain (VAS)	-	NS
			Disability (QBPDS)	-	NS
Newton-John et al., 1995 [41]	PVM control exercises with EMG-FB. 8 sessions, 2x/week.	Waiting list	Pain (NPRS)	1.19	< 0.007
			Disability (PDI)	0.85	< 0.003
Nouwen et al., 1983 [42]	PVM control exercises with EMG-FB. 15 sessions, 5x/week.	Waiting list	Pain (5-point scale)	0.36	NS
Stuckey et al., 1986 [45]	PVM control exercises with EMG-FB. 8 sessions.	Placebo-FB	Pain (VAS)	0.79	NS
			Disability (ADL-Q)	-0.16	NS

All results are post-intervention, unless otherwise reported: *= intermediate term. Positive effect sizes are in favor of the TSET-group. When it was not possible to calculate an effect size, this is indicated with a hyphen (-). For *p*-values: All values are for between group comparisons, NS= non-significant. ADL= activities of daily life, EMG= electromyography, ES= Hedges' g effect size, FB= feedback, MPQ= McGill pain questionnaire, NPRS= numeric pain rating scale, PDI= Pain disability questionnaire, PVM= paravertebral muscle, QBPDS= Quebec back pain disability index, RMQ= Roland Morris disability questionnaire, RPMS= repetitive peripheral magnetic stimulation, TrA= Transversus abdominis muscle, VAS= visual analogue scale.

4 Discussion

The aims of this review were to give an overview and to assess the effectiveness of the available TSET-programmes for patients with LBP. Twenty-five RCTs were included that compared TSET to other forms of rehabilitation, a placebo intervention or no treatment. EMG-FB was used to support exercise therapy in nine papers, while few studies were available for the other technologies.

With regard to effectiveness, the results of this review show that TSET appears to improve pain, disability and quality of life in patients with subacute and chronic LBP, but seems not to provide beneficial effects for patients with acute LBP. When a TSET-programme was added to a standard treatment, this was superior to a standard treatment alone. In most cases, however, TSET did not yield better results compared to other interventions or a placebo intervention (sham FB). Furthermore, when the technological support was the single difference between interventions, no between group differences could be found. One explanation for the lack of additional benefit from technological support, might be that these TSET-programmes mostly adopted a narrow approach to exercise therapy, i.e. training of one particular function of a specific muscle or muscle group. For example, four out of seven studies comparing TSET to a placebo intervention used sEMG-FB to control paravertebral muscle activity and one study used a single session of transversus abdominis muscle training. Although alterations in paravertebral sEMG[49] and transversus abdominis muscle function[50,51] have been reported in patients with CLBP, it can be questioned whether these minimal interventions are sufficient to improve complex problems such as CLBP.

There is growing consensus that exercise therapy for LBP should be tailored to the patient's specific needs.[52-54] This implies that functional exercises, relevant for the individual patient have to be integrated in the rehabilitation process. Only one RCT[35] could be retrieved that incorporated technology into this functional approach, and therefore, the implementation of technological systems into functional movements or activities poses an important challenge. In this respect, O'Sullivan et al.[55] showed that patients with sitting-related CLBP experienced less pain when they received real-time postural feedback while watching a DVD, which was associated with an altered sitting behaviour. In an attempt to reduce flexion postures and movements, Ribeiro et al.[56] investigated the effects of a wearable posture-monitor providing feedback on spinal flexion positions during daily life. Subjects receiving constant feedback significantly reduced spinal flexion after a 4-week intervention period. So, although there is evidence that real-time postural feedback from technological systems can improve spinal posture and reduce aggravating movements during daily life, its long term benefit on pain and disability needs further investigation.

The combination of a standard treatment with a TSET-programme was superior to a standard treatment alone. This is in line with other research showing that a multimodal intervention leads to better outcomes than a unimodal intervention for patients with CLBP.[57] However, it should be noted that in five out of eight studies the standard treatment alone did not lead to significant improvements.[25,28-30,35] Adding a TSET-programme to these ineffective treatments clearly improved pain (ES range= 0.27, 1.87) and disability (ES range= 0.76, 1.27).[28-30,35] The additional benefits of a TSET-programme were less obvious when the standard treatment alone was already effective (ES_{pain}= 0.76, $ES_{disability}$= 0.06).[15,38,47] These results highlight the importance of including a form of (technology-supported) exercise therapy in the rehabilitation of patients with LBP. The supplementary effects might be more pronounced in patients who did not improve by means of their previous treatment, but are more likely to depend on the patient population and the content of both the (technology supported) exercise therapy and the standard rehabilitation. Indeed, some patients may not respond well to exercise therapy,[58] and might be better off with other types of treatment.[59]

Because the available technologies have changed over the years, it might be argued that interventions using more recently developed systems could result in better outcomes. Seven out of ten studies that were published before 2005 used EMG-FB as technological support,[25,26,31,32,41,42,45] whereas only two studies investigated the effects of EMG-FB in the past decade.[24,27] This suggests that a greater variety of technologies is currently available, but may also result from the lack of effectiveness of TSET-programmes using EMG-FB.[25-27,32,41,42,45] Looking at the more recent trials, two smaller studies (n= 60) with a high risk of bias showed that TSET was more effective than other treatments,[24,36] whereas four studies (n= 743), three with a low risk of bias, indicated that there was no difference between interventions.[33,37,40,46] Therefore, our overall conclusion remains that TSET is not more effective than other treatments, also when only recent studies are considered.

4.1 Future directions

The rehabilitation of CLBP is a long process often involving a home-exercise programme. The problem is that up to 50-70% of patients with CLBP do not adhere to home exercise prescriptions.[60,61] Improving these numbers seems warranted, because the level of adherence has been reported to be a predictor of treatment success for patients with CLBP.[18,62] The use of technological applications that support therapy at home may offer an additional value for promoting adherence, as research in other patient populations has shown.[19,20] However, only five of the included studies provided patients with technological support in the home situation,[33-35,37,40] and only two of these studies reported data on adherence to home exercises.[33,37] Hügli et al.[33] showed that there was no difference in time spent on home exercises between subjects who practised in a game-environment and subjects who performed conventional exercises. Krein et al.[37] compared two pedometer-supported walking programmes, where one group had also access to a specific website and received automated feedback messages on walking goals. Only 20-25% of patients logged-in to the website or uploaded pedometer data for more than 80% of recommended times, and this online support did not result in a significant increase in daily walking distance. These results suggest that simply providing patients with LBP with technological support at home does not automatically lead to an improved adherence. Consequently, specific interventions are probably needed.[63]

Treatment effects might also be enhanced by offering reliable feedback on the quality of exercise performance by using technology.[15,16] Patients with CLBP often display altered movement patterns at the spine,[65] making the evaluation and correction of these patterns key components in the rehabilitation.[53] Besides clinical judgement by a therapist,[66] movement patterns can be assessed with kinematic measurements.[15,16] However, the feasibility of kinematic assessment and feedback provision during exercises, especially in the home-environment, is limited because of several reasons. Most of the kinematic assessment tools are complex, require a standardized set-up and are used in laboratory situations. More simple devices have been developed to address these disadvantages, but they may not be suited for precise kinematic assessment during three-dimensional movements.[56,64-66] Of course, it can be argued how precise feedback needs to be in a clinical setting. Rather than constantly keeping a fixed neutral lordosis in the lumbar spine, patients should prevent excessive end range movements and postures.[52] Preliminary results show that the latter can be achieved for movements in the sagittal plane by feedback from portable technological devices.[55,56] Therefore, we believe that these types of technological systems are worthwhile pursuing further.

4.2 Study limitations

Because the field of rehabilitation technology is rapidly changing and we only included RCTs, this review does not provide an exhaustive overview of the available technological systems that support exercise therapy for patients with LBP. Furthermore, 68% of the studies used a CLBP population, and besides EMG-FB, a limited number of studies per technology could be retrieved. This makes it difficult to draw firm conclusions on the effectiveness of the technologies other than EMG-FB, and on the effects of TSET on (sub)acute LBP. Only five studies were found where the technological support was the single difference between the TSET and control intervention. This means that in the majority of the studies, the TSET-programme was compared to a different exercise programme or a non-exercise intervention. Consequently, the results on the additional effects of the technological support itself could only be based on few studies. Finally, about half of the studies had a high risk of bias and an adequate power-calculation was lacking in most of the papers, limiting the strength of our conclusions.

5 Conclusions

The additional benefit from technological support on pain, disability and quality of life is limited, also when only recently published trials are considered. Only the addition of a complementary TSET-programme to a standard treatment resulted in significantly greater improvements on these outcomes. The lack of supplementary effectiveness of technological systems may partly be explained by the fact that the current technologies are mostly used during analytical exercises and are not introduced into functional rehabilitation or in the home environment.

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Additional File 1 detailed search strategy Pubmed

(((((((((((((((((((((((((((((low back pain[MeSH Terms]) AND feedback[MeSH Terms])) OR ((low back pain[MeSH Terms]) AND biofeedback[MeSH Terms])) OR ((low back pain[MeSH Terms]) AND internet[MeSH Terms])) OR ((low back pain[MeSH Terms]) AND therapy, electrical stimulation[MeSH Terms])) OR ((low back pain[MeSH Terms]) AND ultrasonography[MeSH Terms])) OR ((low back pain[MeSH Terms]) AND technology[MeSH Terms])) OR ((low back pain[MeSH Terms]) AND exercise therapy[MeSH Terms])) OR ((low back pain[Title/Abstract]) AND feedback[Title/Abstract])) OR ((low back pain[Title/Abstract]) AND biofeedback[Title/Abstract])) OR ((low back pain[Title/Abstract]) AND internet[Title/Abstract])) OR ((low back pain[Title/Abstract]) AND whole body vibration[Title/Abstract])) OR ((low back pain[Title/Abstract]) AND electrical stimulation[Title/Abstract])) OR ((low back pain[Title/Abstract]) AND ultrasonography[Title/Abstract])) OR ((low back pain[Title/Abstract]) AND ultrasound[Title/Abstract])) OR ((low back pain[Title/Abstract]) AND technology[Title/Abstract])) OR ((low back pain[Title/Abstract]) AND motor control[Title/Abstract])) OR ((low back pain[Title/Abstract]) AND exercise therapy[Title/Abstract])) OR ((low back pain[Title/Abstract]) AND robot*)) OR ((low back pain[Title/Abstract]) AND telemedicine))) OR ((low back pain[MeSH Terms]) AND robotics[MeSH Terms])) OR ((low back pain[MeSH Terms]) AND telemedicine[MeSH Terms]))) OR (((low back pain[MeSH Terms]) AND exercise therapy) AND technology)) OR ((low back pain[Title/Abstract]) AND virtual reality)))) OR ((((low back pain[Title/Abstract]) AND smartphone)) OR ((low back pain[Title/Abstract]) AND mobile app*)) OR ((low back pain[Title/Abstract]) AND sensor[Title/Abstract]))

Additional File 2 Study characteristics categorized by TSET

Study	Subjects	TSET-intervention	comparison	outcomes	outcome times
EMG-feedback					
Ahmed et al., 2013 [24]	CNSLBP > 3 months. Male subjects between 30-40 years, n = 30.	Stabilization and strengthening exercises with Swiss ball. Feedback was given using surface-EMG from rectus abdominis muscle and upper and lower back extensors. Subjects received auditory feedback if the criterion value for maximal muscle contraction was reached. Patients performed a 6-week intervention, with 2 sessions of 40 minutes a week.	Stabilization exercises with Swiss ball without feedback. Patients performed 6-week intervention, with 2 sessions of 40 minutes a week.	Pain: VAS.	At week 2, 4 and 6 of the intervention.
Asfour et al., 1990 [25]	CNSLBP of myofascial origin. Age 44.9 years (mean), male and female, n = 30.	Standard rehabilitation programme + trunk extensor strengthening with EMG-BF (criterion performance level). Patients received 8 sessions of BF-training in 2 weeks.	Standard rehabilitation programme for 2 weeks.	Pain: VAS.	At the end of the 2-week intervention.
Bush et al., 1985 [26]	CNSLBP > 2 years, with at least 2 episodes of LBP a week. Age between 20 – 65 years, male and female, n = 72.	Increase and decrease of EMG-signals from PV musculature. 10 minutes without FB, and 20 minutes with EMG-FB. Patients attended a minimum of 8 sessions. Patients were asked to practise at home without FB.	1. Placebo-group: patients were asked to stabilize their back temperature. 10 minutes with sham-BF and 10 minutes without FB. Patients were asked to practise at home without FB. 2. Waiting list-group.	Pain: VAS, MPQ	Post-treatment and at 3 months follow-up.
de Sousa et al., 2009 [27]	CNSLBP > 3 months. Age = 46.4 years (mean), male and female, n = 60.	Abdominal strengthening exercises with EMG-FB and back stretching exercises. Patients attended 16 session in a period of 8 weeks. Surface-electrodes were placed on upper and lower abdominal muscles and lumbar PV-muscles.	Waiting list.	Pain: VAS. Disability: RMQ.	Post-treatment.

Additional File 2 *Continued*

Study	Subjects	TSET-intervention	comparison	outcomes	outcome times
Newton-John et al., 1995[41]	CNSLBP > 1 year. Age between 18-55 years (mean = 38 years), male and female, n = 36.	Exercises with EMG-FB to restore paravertebral muscle balance, i.e. increase muscle activity on the 'low' side. Patients attended 10 sessions of 35 minutes.	1. Relaxation group: patients received 10 sessions of 35 minutes of relaxation exercises (tension and relaxation of different muscle groups). 2. education group: patients received information on pain, LBP, posture, anatomy and stress during 10 sessions of 35 minutes.	Pain: VAS, MPQ.	Post-treatment and follow-up after 90 days. Long term follow up after 4 years by telephone for the outcome pain.
Hasenbring et al., 1999 [32]	Patients with acute sciatica because of disc herniation and a high risk for chronicity. > 20 years old (mean = 42.7 years), male and female, n = 59.	Standard physiotherapy + EMG-FB training: EMG-FB training was done in sitting, and patients were asked to relax the lumbar PV-muscles. Patients heard clicks at a pace proportional to activity of the lumbar PV muscles. They were also asked to implement this training in daily stressful situations. Patients attended 12 sessions of 20 minutes, one session a week.	1. standard physiotherapy + risk based CBT: a tailored CBT programme was offered, with a minimum of 10 and a maximum of 40 sessions (mean = 27). 2. High risk usual care group: patients with a high risk of chronicity receiving usual care 3. low risk usual care group: patients with a low risk of chronicity receiving usual care 4. Standard physical therapy group	Pain: VAS. Disability: immobility during daily life questionnaire.	Post-treatment and follow-up at 6 months for all groups. Additional assessments at 3, 12 and 18 months for EMG, CBT and standard physical therapy group.
Newton-John et al., 1995 [41]	CNSLBP > 6 months, with a score higher than 5 on the pain index. Age between 18-65 years (mean = 45.7 years), male and female, n = 44.	Criterion-oriented EMG-FB training to reduce muscle activity of ES. 8 sessions of 1 hour, 2 times a week. Also education on stress, muscle tension and relation to pain.	1. CBT-group: 8 sessions of 1 hour, 2 times a week. CBT consisted of pain education, goal and activity setting techniques, autogenic relaxation, breathing exercises and pain control techniques. 2. Waiting list	Pain: pain diary with 10-point likert scale. Disability: PDI.	Post-treatment and 6 months follow-up.
Nouwen, 1983 [42]	CNSLBP > 6 months with high levels of ES-EMG in standing. Age between 20-55 years (mean = 45.7 years), male and female, n = 20	EMG-FB training to reduce muscle activity at lumbar PV-muscles in a standing position. Patients attended 15 sessions over a period of 3 weeks. No home exercises. Surface electrodes were placed at PV-muscles at L4 level.	Waiting list.	Pain: 5-point scale.	Post-treatment.

Additional File 2 *Continued*

Study	Subjects	TSET-intervention	comparison	outcomes	outcome times
Stuckey et al., 1986 [45]	CLBP > 6 months. Age = 41.1 years (mean), male and female, n = 24.	Reducing muscle tension with visual and auditory EMG-FB from upper trapezius muscle and PV muscles. Patients attended 8 sessions of 45 minutes.	1. Relaxation group: Relaxation training with instructions from a therapist to reduce tension of upper trapezius and PV muscles, without EMG-FB. 2. Placebo group: relaxation exercises, but without instructions. Both groups received 8 sessions	Pain: VAS, VAS during functional tests. Disability: ADL-questionnaire.	Post-treatment.
Real-time ultrasound feedback					
Hides et al., 1996 [15]	First episode of non-specific acute unilateral LBP for less than 3 weeks with restricted ROM. Age between 18 – 45 years (mean = 30.9 years), male and female n = 41.	Medical management and isometric MF contraction with co-contraction of deep abdominal muscles in a neutral standing position. RUSI was used for feedback on MF muscle contraction. Intervention for 4 weeks, twice a week	Medical management: advice on bed rest (1-3 days) and absence from work. Prescription of minor analgesics	Pain: VAS, MPQ, pain diary. Disability: RMQ.	Weekly for the first 4 weeks. Follow up at 10 weeks.
Unsgaard-Tøndel et al., 2010 [46]	CNSLBP > 3 months with pain between 2 and 8 on a VAS-scale (0-10). Age between 18-60 years (mean = 40 years), male and female, n = 109.	8 weeks of TrA training using ADIM with co-contraction of pelvic floor and MF. RUSI feedback was used for TrA. One session of 40 minutes per week. Home exercises of 10 repetitions of 10 sec holds (2-3 times a day) were prescribed.	1. Sling exercise: Stabilizing lumbar spine in neutral position with support from elastic bands, while performing arm and leg movements. 2. General exercise: strengthening with fitness machines and stretching in group sessions. One session of 1 hour per week for 8 weeks.	Pain: NPRS. Disability: ODI.	Within the first week after the intervention.

Additional File 2 *Continued*

Study	Subjects	TSET-intervention	comparison	outcomes	outcome times
Internet mediated exercise programmes					
del Pozo-Cruz et al.,2012 [29,30]	Subacute NSLBP, between 6-12 weeks. Patients had to be physically inactive and work at a computer > 6 hours/day. Age between 18-64 years (mean = 46.2 years), male and female, n = 100.	Standard preventative occupational care + a 9-month web-based exercise programme: Patients received an e-mail on working days with a link to an online video containing an 11-minute exercise programme. This programme consisted of postural education, and strengthening, stretching and mobility exercises.	Standard preventative occupational care: general medical examination at least once a year by the university preventative medicine services and access to a website containing information on occupational self-care at the workplace.	del Pozo-Cruz et al., 2012: Disability: RMQ. Quality of life: EQ-5D-EL del Pozo-Cruz et al., 2012: Disability: ODI. Quality of life: EQ-5D-EL	Post-treatment.
Krein et al., 2013 [37]	Veterans with CNSLBP > 3 months, self-reported sedentary life-style and weekly access to a computer. Age > 18 years (mean = 51 years), male and female, n = 229.	A 12-month pedometer-based walking programme with online support: patients had to upload pedometer data and then received personalized automated goals for increasing the number of daily steps via a website. The website also contained videos of back exercises, personalized feedback and general information on back pain. Patients could also participate in an online e-community to discuss topics on back pain and walking strategies in particular. This community was also used by the researchers to encourage patients to achieve the walking goals.	A 12-month walking programme without online support: Patients also used a pedometer and uploaded the data, but they did not receive walking goals. The patients had limited access to the website, so they could only fill in the questionnaires and report adverse events. The control group did not participate in the e-community.	Pain: VAS. Disability: RMQ. Quality of life: SF-36	At 6 months and 12 months.

Additional File 2 *Continued*

Study	Subjects	TSET-intervention	comparison	outcomes	outcome times
Whole body vibration					
del Pozo-Cruz et al., 2011 [28]	CNSLBP > 6 months, physically inactive. Age between 40-70 years (mean = 59.1 years), male and female, n = 50.	Standard medical care at public health institute + WBV-training: Standing on a WBV-device with knees bent. Increase in training duration over course of programme. 12 weeks of training, 2 times a week.	Standard medical care at public health institute. Continuation of normal ADL-pattern.	Pain: VAS. Disability: RMQ, ODI. Quality of life: EQ-5D-EL	Post-treatment.
Rittweger et al., 2002 [44]	CNSLBP > 6 months continuous or > 2 year intermittent. Age between 40-60 years (mean = 52 years), male and female, n = 60.	Pelvic tilts and slow torso movements on a WBV-device. Exercise time increased to a maximum of 7 minutes and weights on the shoulders were added. 18 sessions in 12 weeks.	Strengthening exercises for lumbar extensors, abdominal muscles and thigh muscles. 18 sessions in 12 weeks.	Pain: VAS. Disability: PDI.	Post-treatment. PDI also at 6 months follow-up.
Yang et al., 2015 [47]	CNSLBP > 3 months. Mean age = 31.9 years, male and female, n = 40.	Static and dynamic lumbar stability training in lying position using PBU. Five minutes of WBV-training. 18 sessions in 6 weeks.	Static and dynamic lumbar stability training in lying position using PBU. 18 sessions in 6 weeks.	Pain: VAS Disability: ODI	Post-treatment
Nintendo Wii-exercises					
Kim et al., 2014 [36]	LBP > 2 months, middle-aged women (mean age 47.4 years), n = 30.	Wii fit yoga programme consisting of 7 exercises of 3 minutes. 12 sessions of 30 minutes in 4 weeks.	30 minutes of trunk stabilization + 30 minutes standard physical therapy. No information on number of treatments.	Pain: VAS. Disability: RMQ, ODI.	Post-treatment.
Park et al., 2013 [43]	Industrial workers with work-related CLBP > 3 months. Age = 44.3 years (mean), n = 24.	30 minutes of Physical therapy + 30 minutes of Nintendo Wii sports programme. Wii-programme consisted out of 4 games. Subjects could choose which game they played. 3 sessions per week, for 8 weeks.	1. Stabilization group: 30 minutes of physical therapy + 30 minutes of lumbar stabilization exercises. 2. Physical therapy group: 30 minutes of therapeutic US, hot packs, interferential current. Both groups had 3 sessions per week, for 8 weeks.	Pain: VAS. Quality of life: RAND-36	Post-intervention.

Additional File 2 *Continued*

Study	Subjects	TSET-intervention	comparison	outcomes	outcome times
Postural feedback					
Hügli et al., 2015 [33]	NSLBP > 4 weeks. Age between 18-65 years (mean 36.5 years), male and female, n = 20.	Motor control exercises + manual therapy. Patients received augmented FB from motion sensors during exercises, and also practised at home with the FB system. FB was given on exercise performance. Patients received 9 sessions.	Same treatment as the intervention group, but without FB. Patients received 9 sessions.	Disability: ODI, PSFS	Post-intervention
Kent et al., 2015 [35]	NSLBP >3 weeks, with motor control impairment and pain on VAS >3/10. Age between 18-65 years, male and female, n = 112.	Guideline-based physical therapy + motor control exercises with FB from motion sensors and PV EMG. Patients received 6-8 sessions over a 10-week period to change movement patterns and posture during which they received postural FB. After each session, the patients wore the sensors for 4-10 hours at home to provide FB on their posture and movement. Home exercises were performed without the sensor-FB.	Guideline-based physical therapy. 6-8 sessions over a 10-week period	Pain: QVAS Disability: RMQ, PSFS	Week 1, 3, 6, 8, 10 of treatment. Follow-up at 3, 6 and 12 months.
Magnusson et al., 2008 [38]	CNSLBP > 6 months. Age between 20-70 years (mean = 52.3 years), male and female, n = 47.	Patients followed a standard rehabilitation + a motor learning programme with a motion-tracking device. Motor learning programme: patients had to move the spine, represented by an icon on a screen, in 3 planes to bring the back icon to a certain position which was showed on the screen. Auditory and visual FB + success rate FB was given. Patients attended 10 sessions in 5 weeks, 30’ per session (15 minutes of effective training).	Standard rehabilitation: weekly 1-hour sessions for 5 weeks containing postural education, advice to stay active, strengthening and mobility exercises and self-management strategies.	Pain: VAS. Quality of life: SF-36	Post-intervention. Follow-up at 6 weeks and 6 months.

Additional File 2 *Continued*

Study	Subjects	TSET-intervention	comparison	outcomes	outcome times
Respiratory feedback					
Kapitza et al., 2010 [34]	Moderate CNSLBP of myofascial origin > 3 years. No concurrent TENS-treatment, no experience with relaxation. Age between 18-70 years (mean = 53.6 years), male and female, n = 42.	Home based breathing exercises with respiratory FB device. Synchronized optical and auditory FB of breathing pattern. 15 days of 30 minute sessions.	Home based breathing exercises with respiratory FB device. Sham (non-synchronized) optical and auditory FB of breathing pattern. 15 days of 30 minute sessions.	Pain: VAS. Disability: PDI.	Post-treatment. Follow-up at 2 weeks and 3 months.
Repetitive peripheral magnetic stimulation					
Massé-Alarie et al., 2013 [39]	CNSLBP > 1 year and no abdominal training in the past year. Age between 30-70 years (mean = 53.6 years), male and female, n = 13.	Single session of RPMS alone (10 min of intermittent stimulation, 2 cm medial of ASIS), followed by TrA training with concurrent RPMS. TrA training in crook lying, 10 repetitions of 10 second holds at 15% of MVC (EMG FB)	Single session of sham RPMS alone, followed by TrA training with concurrent sham RPMS. TrA training in crook lying, 10 repetitions of 10 second holds at 15% of MVC (EMG FB)	Pain: VAS. Disability: QBPDS.	Pain: post-intervention Disability at 2 weeks follow-up.
Video-supported exercise therapy					
Miller et al., 2004 [40]	LBP patients referred for individual physical therapy and access to a video-player. Age > 16 years (mean = 44.3 years), n = 385.	Patients followed individual physical therapy. Group 1 also received a video with exercises demonstrated by their treating physical therapist. Group 2 received a video with exercises demonstrated by an anonymous therapist. In both groups, videos were taken home to support home exercises. ±4 sessions in 4-6 weeks.	Patients received physical therapy and only face-to-face demonstration of the exercises. ±4 sessions in 4-6 weeks.	Disability: RMQ. Quality of life: SF-36	4-6 weeks after randomization.

ADIM: abdominal draw-in maneuver; CNSLBP: chronic non-specific low back pain; EMG: electromyography; EQ-5D-EL: European quality of life-5 dimensions-3 levels; ES: erector spinae; FB: feedback; LD: latissimus dorsi muscle; MF: multifidus; MPQ: McGill pain questionnaire; MVC: maximal voluntary contraction; NPRS: numeric pain rating scale; ODI: Oswestry disability index; OE: obliquus externus; OI: obliquus internus; PV: paravertebral; PDI: pain disability index; PSFS: Patient specific functioning scale; QBPDS: Quebec back pain disability index; QVAS: Quadruple pain visual analogue scale; RAND-36: RAND-36 health status inventory; RMQ: Roland Morris Questionnaire; RPMS: repetitive peripheral magnetic stimulation; SF-36: Shortform-36; TrA: transversus abdominis; TSET: technology-supported exercise therapy; VAS: visual analogue scale

Study 1 bis

The effectiveness of technology-supported exercise therapy for low back pain: a systematic review.

Response to the letter to the Editor

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To the Editor:

We would like to thank dr. Kawada for his interest in our research and his comments on our paper entitled 'The effectiveness of technology-supported exercise therapy for low back pain: a systematic review.'[1]

In his letter, dr. Kawada suggested to perform a meta-analysis. The main reason for not performing a meta-analysis was the heterogeneity of the included studies, as mentioned in the paper and recommended by the guidelines for Systematic Reviews in the Cochrane Back and Neck Group.[2] The included studies used different forms of exercise therapy and different types of technological support. Therefore, we provided effect sizes of individual studies instead of pooled results.

The author highlighted the importance of pain neurophysiology education and cognitive behavioural therapy (CBT) in the treatment of patients with chronic low back pain. Accordingly, he stated that the effectiveness of technology-supported exercise therapy (TSET) should be assessed simultaneously with pain education and CBT. We agree that it is essential to include a cognitive component, such as pain neuroscience education (PNE), in the rehabilitation of patients with chronic low back pain. The rehabilitation programmes of some of the studies that were included in the review did contain an educational component. However, the education focused on a more traditional back school approach, i.e. information on posture, advice to staying active and anatomy. No studies were found that used TSET in combination with a modern PNE approach (e.g. as described by Nijs et al.[3]). This should not come as a surprise since most of the studies investigating the effectiveness of PNE have only been published more recently.[4]

The author indicated that it is important to assess the influence of content and dose on the effectiveness of the TSET-programmes. As mentioned before, the content of the TSET-programmes and their comparisons varied greatly. In the discussion section of our paper, we clearly described that the lack of additional benefit from technological support may be explained by the content of the TSET-programmes. For example, most of the papers that compared TSET to a placebo treatment used a very narrow approach to exercise therapy, that is, only the function of one particular muscle (group) was trained (e.g. transversus abdominis muscle). It is unlikely that such a minimal intervention will improve a multifactorial problem such as chronic low back pain. Moreover, there is growing consensus that exercise therapy should be tailored to the patient's individual needs and incorporated in functional activities.[5,6]

To investigate the effect of the dose, a separate analysis was performed regarding the effects of a standard treatment and TSET to a standard treatment alone. This separate analysis proved valuable, because adding a TSET-programme to a standard treatment was superior to a standard treatment alone, whereas a TSET-programme alone was not better than another intervention. Looking at the studies that compared TSET to another intervention or a placebo, 14 out of 16 studies (88%) used the same number and duration of treatment sessions in the TSET and control group. One paper (6%) did not clearly describe the number of treatments in the control group. When considering dose, home exercises should also be taken into account. Four out of sixteen (25%) papers provided a home exercise programme. Two of these studies reported results on adherence, and did not find a significant difference between TSET and conventional exercise therapy. Therefore, the number and duration of supervised treatment sessions, as well as the adherence to home exercises are highly unlikely to have influenced the results of the comparison between TSET and other interventions.

In conclusion, there are many aspects that still need to be clarified when it comes to TSET for low back pain. Although it may be useful to evaluate the effects of a PNE and TSET simultaneously, we believe that various elements pertaining to TSET itself should be investigated first. For example, our systematic review shows that the integration of technological systems in an individual approach and home exercises is currently lacking, which may explain why TSET was not found to be more effective than conventional exercise therapy. In addition, some types of technological support (e.g. postural feedback) might be more effective than others (e.g. EMG-feedback). Future research should evaluate the feasibility of introducing technology in an evidence-based approach to exercise therapy and focus on the underlying principles of technological support. Gaining more insight into the optimal way of providing technological support (e.g. type of feedback, methods to increase adherence and motivation) may provide valuable information to enhance the effectiveness of technology-supported exercise therapy for low back pain.

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Study 2

Serious gaming to support exercise therapy for patients with chronic nonspecific low back pain: a feasibility study

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Abstract

Objective: To investigate the feasibility of a functional exercise programme supported by serious gaming for patients with chronic nonspecific low back pain.

Materials and Methods: Ten patients with chronic nonspecific low back pain and an underlying movement control impairment were recruited. Subjects performed a partially supervised exercise programme (36 sessions, 18 weeks) that included 30 minutes of general conditioning and 90 minutes of individually tailored functional movement control exercises. Serious games were used to (1) improve thoracolumbar dissociation and (2) to provide postural feedback during functional movement control exercises. The serious games were also available at home.

Results: Treatment satisfaction and the scores on the credibility/expectancy questionnaire were good and did not change throughout the intervention. Patients remained motivated throughout the rehabilitation programme and no serious adverse events were reported. Overall, participants indicated that the serious games helped them to perform the home exercises more correctly, and as a consequence, they felt more confident doing them. However, the time needed to set up the games was a barrier for home-use and participants would have found it useful to receive postural feedback during daily life activities.

Conclusions: It is feasible to support a functional exercise programme with serious games for patients with chronic nonspecific low back pain, both in a supervised and a home environment. Time-efficiency and the integration of serious games in daily life activities are challenges that need to be addressed in the future.

1 Introduction

Low back pain (LBP) is one of the most common health problems in Western society[1] and has a substantial impact on daily functioning.[1,2] Globally, it is the leading cause of disability[1] and it is one of the most important reasons for work absenteeism.[3] When the pain persists for more than three months, it is defined as chronic low back pain (CLBP).[4]

Exercise therapy is often the treatment of choice for patients with CLBP. Although this type of intervention has been proven to be effective in reducing pain and disability, the effect sizes are only small to moderate.[4,5] One of the main reasons for the modest results is that exercise programmes are not in line with the current recommendations for exercise therapy,[6] namely that exercises should be supervised (individually or in group),[7] integrated in functional tasks,[8,9] and tailored to the patient's individual needs[6-8,10] and preferences.[7,11,12] In addition, the barriers to participate in an exercise programme should be addressed.[12] Examples of these barriers are poor motivation,[13-15] lack of support during (home) exercises[14,15] and fear about incorrect exercise performance.[12,15]

Innovative approaches, such as the use of rehabilitation technologies, could potentially overcome some of these barriers.[16] However, previously investigated technologies show two major weaknesses, namely the lack of gaming aspects (e.g. fun or competition)[17] and the fact that most technologies were initially developed for other purposes than to support exercise therapy for LBP (e.g. diagnostic ultrasound).[16] The possible applications of these systems are therefore limited, which implies that they are typically being used during standard exercises in non-functional positions (e.g. transversus abdominis training in lying).[18,19] Moreover, these technologies cannot be used at home,[16,20] whereas home-based exercises are essential in the rehabilitation of patients with CLBP.[21,22] Serious games (SGs) specifically designed for LBP rehabilitation might address the shortcomings of current technologies. As SGs have the purpose to train new skills or develop new knowledge in a fun and engaging way,[17,23] they have the potential to increase motivation and adherence,[20,24,25] which can be an important pathway for the improvement of treatment effects.[21,22] Secondly, SGs are capable of providing postural feedback in the absence of a therapist and can inform patients about a correct exercise performance, supporting them during their home exercises.

Studies integrating SGs into a tailored and functional rehabilitation programme including home exercises are currently lacking for patients with CLBP, in part because most technological systems are not suited to support this type of rehabilitation.[16] In addition, patients with CLBP typically need to continue exercising for a longer period,[11] while the motivating effects of SGs might decrease over time.[26] Hence, it remains questionable whether SGs can be successfully integrated in a long-term rehabilitation programme. Therefore, it is worthwhile investigating the feasibility of such an intervention. Accordingly, the primary aims of this feasibility study were: (1) to assess the treatment credibility and expectancy of improvement, (2) to evaluate patients' motivation for a long-term SG-supported exercise programme, (3) to assess the feasibility of using SGs at home, and (4) to monitor adverse events. The secondary aim was to evaluate the effectiveness of the programme.

2 Methods

2.1 Participants

Ten patients who participated in an outpatient rehabilitation programme for LBP were recruited at the Jessa Hospital, Belgium. To be included, subjects had to be between 18 and 65 years old, diagnosed with chronic nonspecific LBP (> 3 months), and with an underlying movement control impairment. The diagnosis of a movement control impairment was based on a comprehensive assessment, which is described elsewhere.[27,28] Exclusion criteria were: spinal surgery in the past, presence of an underlying serious pathology (e.g. inflammatory diseases), signs or symptoms of nerve root involvement, pregnancy (up to one year postpartum) and an allergy for tape. The study was approved by the medical ethical committees of the Jessa Hospital and of Hasselt University (Hasselt, Belgium). All patients gave written informed consent before being included in the study.

2.2 Technological system – serious games

The ValedoMotion®system (version 1.2, Hocoma, Switzerland) is a rehabilitation tool for patients with LBP. It consists of a laptop, remote control and three inertial wireless motion tracking sensors (40x30x16 mm, ±16 g). Two sensors are mounted to the patient's spine at the L1 and S1 level (Fig. 1), while one sensor is used to calibrate the system. The sensor signals are sent to the laptop, enabling the patient to practise pelvic tilt exercises in a gaming environment (Fig. 2). The system uses the movements of the S1-sensor relative to the L1-sensor to control the games. In this way, patients have to dissociate lumbopelvic movements from the thoracic spine. Secondly, patients can receive feedback during functional movement control exercises (MCEs) using the 'target game' and the 'coconut game'. The target game is displayed as a bull's eye and the coconut game as a tray with coconuts (Fig. 3). The sensors detect the spinal movements and the cursor on the screen (target game) or the tray (coconut game) will move accordingly. When patients are able to control the lumbopelvic movements, they can keep the cursor in the middle of the bull's eye or prevent the coconuts from falling off the tray.

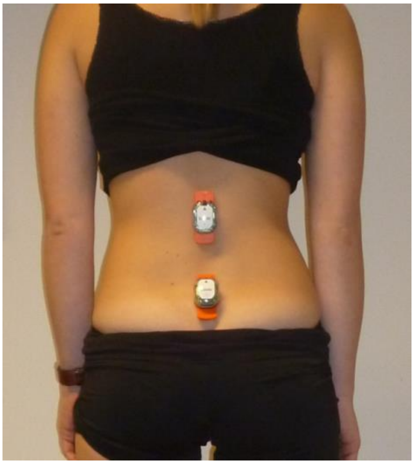

Fig 1 Sensor placement

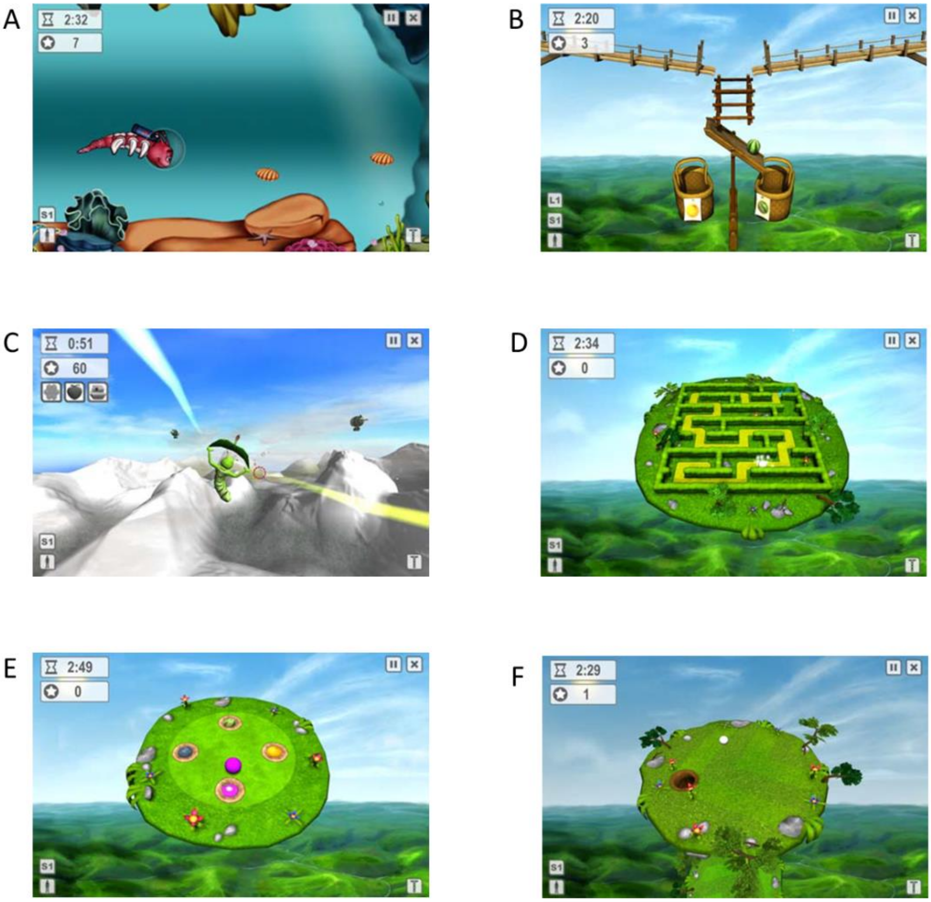

Fig 2 Serious games for pelvic control and thoracolumbar dissociation. **A**. Cavediver, for pelvic movements in the sagittal plane. **B**. Fruits, for pelvic movements in the frontal plane**. C-F**. Glider, Maze Square, Colours and Golf, for 3D pelvic movements.

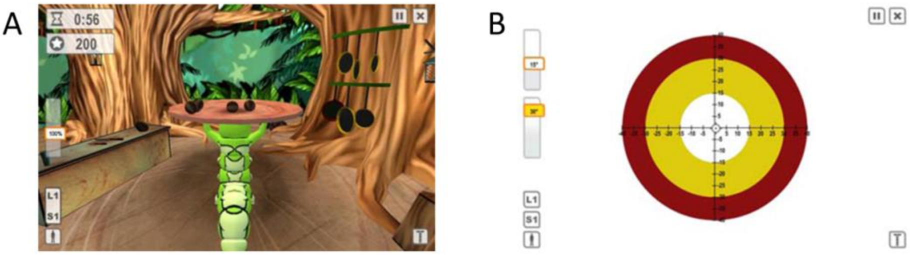

Fig 3 Serious games for postural feedback during functional movement control exercises. **A**. Coconut game. The difficulty of the game could be adjusted so that less lumbar movement was allowed before the coconuts fell of the tray. **B**. Target game.

2.3 Intervention

A detailed description of the intervention can be found in the Additional File. Subjects participated in an outpatient rehabilitation programme for LBP that consisted of 36 sessions at a hospital (two hours, twice weekly) and home exercises. Subjects performed a tailored functional exercise programme including 30 minutes of general conditioning and 90 minutes of MCEs under partial supervision. During the first three weeks, patients practised without technological support (standard rehabilitation), after which the technological support was gradually introduced (see Table 1). Patients were asked not to participate in any other form of rehabilitation during the study.

Outcome measures were obtained at baseline and at the end of week 3, 8, 13 and 18 (i.e. at the end of the intervention).

Table 1 Summary Serious games supported exercise therapy programme

	Exercise programme	Serious games?
Week 1-3	General conditioning	No
	Movement control exercises	No
	Home exercises	No
Week 4-5	General conditioning	No
	Movement control exercises	Yes
	Home exercises	No
Week 6-13	General conditioning	No
	Movement control exercises	Yes
	Home exercises	Yes
Week 14-18	General conditioning	No
	Movement control exercises	No
	Home exercises	No

2.3.1 Standard rehabilitation

The general conditioning included cycling on a stationary bike at an intensity of 75% of the maximal heart rate, and exercises on a stepping machine and crosstrainer.

A summary of the MCE protocol is provided in Table 2. All patients were treated according to these principles, but the exercises were tailored to the patient's specific problem (Fig. 4).

Table 2 Description of the different stages of the functional movement control exercise protocol

Education	Explanation of key-concepts of movement control exercises: kinesiopathologic model, neutral spinal position.
Pelvic tilts in different directions	Emphasis on a correct dissociation between lumbar and thoracic spine.
Postural education and repositioning exercises	Education about a neutral spinal position in sitting, standing or other functional positions, depending on the patient's needs. Repositioning exercises: patients were asked to assume their neutral spinal position or were placed in this position by the therapist. Then, they were asked to move out of this position, and to return back to the neutral position.
Retraining of static stability	Patients learned how to keep their lumbar spine in a neutral position during a variety of exercises and functional movements. These movements were based on the patient history, physical examination and the patient's rehabilitation goals. If necessary, functional activities were first divided into more analytical movements (segmentation) and performance was made easier by training in unloaded positions and at slower speeds (simplification). Analytical exercises were integrated into functional movements as soon as possible.
Retraining of dynamic stability	The same exercises and principles as in the static stability phase were used to retrain the dynamic stability. Instead of keeping the spine in the neutral position, the patient was instructed to move the lumbar spine in the previously painful direction, but with careful consideration not to allow exaggerated movement in the targeted segments.
High level functional retraining	In order to match real-life situations, the following progressions were made: • Increase the number of repetitions • Increase the load (e.g. handling heavier objects or adding resistance) • Increase the holding time for static positions (e.g. manual handling in a waiter's bow position) • Increase training variability (e.g. handling different objects, lifting from different heights) • Handling of real-life objects • Practise on unstable surfaces if necessary • Reduce and omit feedback (e.g. no tactile or visual feedback)

Different stages of movement control training adapted from Hodges et al.[8]

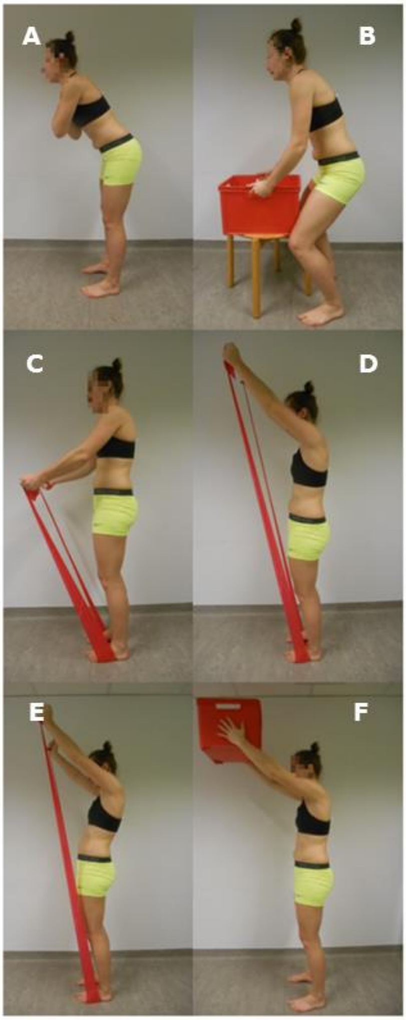

Fig 4 Functional movement control exercises. **A.** Waiter's bow: the patient is asked to bend forward in the hips while keeping the spine in a neutral alignment. **B.** Integration into a functional task: The patient is asked to lift the box with a neutral spinal alignment. The task is facilitated by placing the box on a chair. **C**. Functional exercises to prevent excessive lumbar extension. The patient assumes a neutral spinal alignment. **D.** The patient lift the arms overhead with resistance from an elastic tube, while keeping the neutral spinal position. **E.** Incorrect performance with excessive lumbar extension. **F.** Integration of real-life objects: lifting a box overhead.

2.3.2 Serious game supported rehabilitation

The SG-supported exercise therapy was identical to the standard rehabilitation, except that patients received sensor-based postural feedback from the SGs during 45 minutes of MCEs consisting of thoracolumbar dissociation exercises and functional MCEs. The rest of the time, patients performed the exercises without feedback.

Thoracolumbar dissociation exercises were trained with SGs that had to be steered with pelvic tilts (Fig. 2). All the games were played in a standing or in a sitting position, with a duration of two minutes each. Participants played a selection of five games per session. The difficulty level was adjusted for each game throughout the rehabilitation programme. First, the games requiring single plane pelvic movements were selected, while the games controlled by 3-dimensional movements were added later.

Regarding the functional MCEs, patients continued their standard rehabilitation, but the exercises were supported by postural feedback from the target/coconut game (Fig. 3). To avoid patients becoming dependent on the feedback and to improve the learning process, the amount of feedback was gradually decreased and eventually omitted during the last five weeks of the intervention.[29] This is essential, as patients should learn to control their lumbar spine movements during daily life activities when no extrinsic feedback is available.

2.3.3 Home exercises

Participants were given an exercise booklet that contained pictures and a description of the exercises. Between week six and thirteen they received a ValedoMotion®system to support their home exercises. Participants were asked to perform three SGs and three functional MCEs at home, and to implement the principles they learned during daily life activities.

2.4 Outcome measures

2.4.1 Treatment credibility and expectancy for improvement, motivation, treatment satisfaction and adherence

Treatment credibility and the expectancy for improvement were assessed with the credibility/expectancy questionnaire (CEQ),[30] which consists of the credibility and the expectancy subscales. Both subscales have a total score between 3 and 27, with a higher score reflecting a better result. Training motivation was assessed with the Intrinsic Motivation Inventory (IMI).[31] The IMI consists out of 35 items divided over of six subscales, with a higher score corresponding with a better outcome (range 1-7). Treatment satisfaction was measured with an 11-point scale (0= not satisfied at all, 10= fully satisfied). The adherence towards the treatment programme was measured by the number of attended treatment sessions in the hospital (range 1-36).

2.4.2 Feasibility of unsupervised use of the SGs at home

Therapists recorded the time needed to explain to patients how to use the technological system, the time needed for patients to set up the system themselves, and whether patients were able to place the sensors correctly on the spine.

Using open-ended questions, patients were asked (1) to elaborate on their experiences with the SGs at home, and (2) to indicate how the technological system could be improved. Adherence to home exercises was evaluated with a diary, in which patients were asked to indicate how long they practised each day, and whether they used the SGs.

2.4.3 Adverse events

Patients were asked to report any adverse events (e.g. pain flare-ups) to the therapists. Although serious gaming seems to be a safe way of rehabilitation, adverse events are underreported and few studies have used SGs in unsupervised conditions.[20,24] In addition, experiencing pain during SGs can be a reason for discontinuing the exercises.[20] Therefore, the number of drop-outs, with reasons why, was recorded.

2.4.4 Effectiveness of the programme

Pain was assessed with the numeric pain rating scale (NPRS).[32] This is an 11-point scale ranging from 0 to 10, where patients have to indicate the average intensity of their LBP over the past two days. Disability was assessed with the Roland Morris Questionnaire (RMQ)[33] and the patient-specific functioning scale (PSFS).[34] The RMQ contains 24 questions about the effects of LBP on daily activities, with a higher score (range 0-24) representing a higher level of disability. For the PSFS, the patient has to identify three to five activities that are difficult to perform because of LBP. Each activity is scored on a 0 to 10 scale, with a lower score indicating a higher level of disability. An average score (range 0-10) was calculated from the scores on the individual activities. Kinesiophobia (i.e. fear of movement) was measured with the Tampa scale for kinesiophobia (TSK).[35] This questionnaire contains 17 items to assess subjective ratings of kinesiophobia and fear of re-injury due to physical activity. Quality of life was measured with the Short Form-36 Health Survey (SF-36).[36] The SF-36 consists of 36 items that can be divided into eight subscales and two domains (i.e. a mental and physical health component). A total score for the mental and physical health component was calculated. For the work status assessment, patients had to indicate whether they had a paid job (yes/no), and if so, whether they were on (partial) sick leave because of their LBP (yes/no).

2.5 Statistical Analysis

Because of the small sample size, non-parametric tests for repeated measures were used. A Friedman analysis was used for continuous data, with a Wilcoxon signed rank test as post-hoc analysis. The Cochran's Q test was used to analyze the dichotomous data. The α-level was set at 0.05, with a Bonferroni correction for the post-hoc tests.

An intention-to-treat analysis was performed by using a single imputation technique for dealing with missing data. The mean proportional change between two test occasions was calculated using the available data for that particular outcome. This proportional difference was used to estimate the missing scores for the subject with missing data.

3 Results

Patient characteristics are presented in Table 3. None of the patients received co-interventions during the study.

Table 3 Sociodemographic data

	Median	IQR
Age (years)	35.5	28
Height (m)	1.81	0.2
Weight (kg)	74	12.5
BMI (kg/m²)	22.6	2.0
Duration LBP (years)	8.5	17.6
Sex (male/female)	8/2	
Sick leave (yes/no)	2/6	

BMI= Body mass index, IQR= interquartile range, LBP= low back pain

3.1 Treatment credibility and expectancy for improvement, motivation, treatment satisfaction and adherence

An overview of the results is provided in Table 4. Overall, the scores for treatment satisfaction and on the subscales of the CEQ and IMI were moderate to high at baseline, and high at the end of the (SG-supported) intervention.

3.2 Feasibility of unsupervised use of the SGs at home

It took 20-30 minutes for therapists to explain the system to the patients. After this introduction, all the participants were able to set up and use the system without supervision.

Overall, patients found it positive to have technological support at home. All patients indicated that the postural feedback helped them to perform the exercises more correctly, and as a consequence, they felt more confident doing them. Nine participants considered the SGs to be more motivating and fun than conventional exercises. Six participants reported that towards the end of the rehabilitation, they mainly used the target/coconut game during functional exercises, as they perceived these exercises to be the most useful.

Two main barriers to home use were reported. Although it took only five minutes to set up the system, six patients considered this extra effort as a barrier to use the SGs at home. Secondly, six patients reported that they also preferred to be able to receive postural feedback during daily life activities, such as cleaning or gardening. This would allow them to practise during lunch breaks or job-related tasks.

Because only three participants consistently filled in the home-exercise diary, no conclusions can be drawn regarding the adherence to home exercises.

3.3 Adverse events

One patient reported two episodes of slightly increased pain for several days, but attributed this to a change in working schedule, rather than to the exercises. Apart from a minimal transient increase in pain during exercises, other participants reported no adverse events. One participant dropped out after T1, due to personal reasons, which were not related to the study.

Table 4 Results for credibility and expectancy, motivation and treatment satisfaction (n = 10)

	T0	T1	T2	T3	T4	*p*-value
CEQ[a]						
Credibility	21.5 (5.5)	22 (2.75)	23 (5.8)	23 (5.8)	-	0.63
Expectancy	17.4 (7.3)	20.5 (4.9)	19.7 (5.2)	19.7 (5.4)	-	0.4
IMI[a]						
Interest/enjoyment	4.6 (1.6)	4.9 (1.8)	4.9 (1.7)	5.4 (1.8)	-	0.19
Perceived comp.	3.9 (1.5)	4.5 (2.2)	5.1 (1.4)[b]	5.3 (1.5)[b]	-	0.001
Effort/importance	5.7 (1.6)	5.7 (1.6)	5.9 (1.6)	5.3 (1.2)	-	0.39
Pressure/tension	5 (1.4)	5.4 (0.6)	6.4 (1.5)[b]	6 (0.7)[b]	-	0.002
Value/usefulness	5.9 (1.3)	5.9 (0.7)	6.1 (1.2)	5.9 (1)	-	0.34
Relatedness	5.3 (1.3)	5.8 (0.9)	6 (0.8)	5.4 (1.2)	-	0.079
Satisfaction	-	7 (1.5)	8 (1.5)	8.5 (3.5)	8 (3)	0.51

Data are denoted as median scores (interquartile range). CEQ= credibility/expectancy questionnaire, IMI= Intrinsic Motivation Inventory, Perceived comp.= Perceived competence, Satisfaction= patient satisfaction with the treatment.
Assessment times: T0= baseline, T1= end of week 3, T2= end of week 8, T3= end of week 13, T4= end of week 18 (post-intervention).
a= Baseline scores were obtained after the first session.
b= significant difference compared to baseline ($p < 0.0125$)

3.4 Effectiveness of the programme

Except for the mental component of the SF-36 ($\chi^2 = 1.4$, $p = 0.50$), all other clinical outcomes significantly improved over time. All participants who were on sick leave at baseline had returned to work by the end of the intervention (Table 5).

Table 5 Results for clinical outcomes (n= 10)

	T0	T1	T2	T3	T4	*p*-value
NPRS	5.5 (4.0)	-	3.5 (2.8)	-	2.5 (2.5)[a]	0.011
RMQ	9.5 (5.5)	-	4 (4.5)[a]	-	4 (5.0)[a]	0.004
PSFS	4.7 (1.1)	-	6.8 (3.7)[a]	-	7.8 (3.5)[a,b]	< 0.001
TSK	36.5 (15)	-	31 (12.8)	-	33 (10.5)	0.009
PSEQ	40 (16.5)	-	51 (12.3)	-	54 (12)[a]	0.002
Short form 36						
Physical component	36.4 (9.2)	-	49.5 (11.7)[a]	-	50.1 (11.6)[a]	<0.001
Mental component	58.1 (8.9)	-	57.9 (6.7)	-	58.7 (6.8)	0.5
Sick leave (yes/no)	2/6	-	1/7	-	0/8	0.22
Adherence	-	-	-	-	36 (2.5)	

Data are denoted as median scores (interquartile range), except for the outcome sick leave. NPRS= numeric pain rating scale, RMQ= Roland Morris Questionnaire, PSFS= patient-specific functioning scale, TSK= Tampa scale for kinesiophobia, PSEQ= pain self-efficacy questionnaire, Satisfaction= patient satisfaction with the treatment.
Assessment times: T0= baseline, T1= end of week 3, T2= end of week 8, T3= end of week 13, T4= end of week 18 (post-intervention).
a= significant difference compared to baseline ($p < 0.017$), b= significant difference compared to T2 ($p < 0.017$)

4 Discussion

When offering a new way of rehabilitation, it is valuable to assess the credibility and expectancy of patients towards this approach. Both factors have been shown to be associated with the outcome of a rehabilitation programme for patients with CLBP.[37,38] The results from the CEQ indicate that patients found the SG-supported treatment credible and that they expected the treatment to be effective, and this remained so during the whole intervention. This might be due to the fact that the treatment rationale and the purpose of the SGs were discussed with the patients prior to the start of the intervention.[38] In addition, participants could probably relate the exercises to their specific impairments because of the functional approach that was based on their personal rehabilitation goals. Patients with LBP value this individual care over a standard intervention, and expect it to be more effective.[12,39]

By integrating SGs into a tailored exercise programme, we tried to overcome some important barriers to exercise therapy, such as insufficient support during home exercises,[14,15] low confidence in a correct exercise performance[12,15] and poor motivation.[14,15,40] The participants in our study indicated that they felt supported and more confident about their exercise performance due to the feedback from the SGs at home. With respect to motivation, patients often need extra support (e.g. by a mobile app)[41] to continue exercising.[42] Serious games also have the potential to improve the motivation to exercise,[24,25] but this has mostly been shown in studies lasting only 4-6 weeks.[24,43] Because patients with CLBP typically need to exercise for a longer period,[11] and motivation might decrease over time,[26] we investigated this during an 18-week intervention. The results from our study showed that patients remained motivated and satisfied throughout the intervention. All of the scores on the subscales of the Intrinsic Motivation Inventory were high at the end of the intervention (> 5.3) and none of the scores declined over time. This might explain why the drop-out rate was only 10% (1 patient) and all patients attended >80% of the sessions. Unfortunately, the response rates to the home-exercise diaries were very low, so we cannot make any conclusions about the adherence to the home-exercise programme, which is a limitation of our study.

Research in patients with musculoskeletal pain shows that it is feasible to integrate SGs into rehabilitation programmes.[43] However, most studies only used supervised exercise programmes in hospitals or rehabilitation centers, where the technological system is set up by a therapist.[20,43] For patients with CLBP, home exercises are an important part of the rehabilitation and, as such, technological support should ideally be provided at home.[16] Consequently, patients need to be able to use SGs without supervision. Overall, patients from our study found it feasible to use the system at home. However, although it took only several minutes to set up the system, this was sometimes considered as a barrier to use the SGs at home, especially when time to practise was scarce. In addition, most patients would prefer a system that can be used outside the home environment (e.g. at work). This highlights the need for user-friendly rehabilitation technologies that can be used without spatial constraints (e.g. no need for the proximity of a computer). More, in depth qualitative studies pertaining to patients' experiences with unsupervised use of rehabilitation technologies may provide useful information concerning the requirements for future developments of technologies.

Finally, the small sample size and lack of control group have to be taken into account when interpreting the results of this feasibility study. In particular, the improvements in clinical outcomes should not be overestimated.

5 Conclusions

It is feasible and safe to support a long-term and individually tailored functional MCE programme with serious games during supervised and home exercises. Patients felt more confident while performing the exercises with postural feedback, found the intervention credible and remained motivated throughout the rehabilitation programme. However, these results need to be interpreted with care because of the small sample size and the lack of a control group. Time-efficiency and the integration of serious games in daily life activities are challenges that need to be addressed in the future.

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Author disclosure statement

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Additional File – detailed description of the intervention according to the TIDieR checklist

Part 1: TIDieR checklist

1. Brief name

Serious gaming to support exercise therapy for patients with chronic non-specific low back pain: a feasibility study

2. Why?

A recent systematic review[16] showed that most technology-supported exercise therapy programmes for patients with low back pain (LBP) are lacking essential components:

- Technological support is not provided at home. Because home exercises are a crucial part of a rehabilitation programme for patients with LBP,[21,22] technological support should also be offered during home exercises, especially because no therapist is available to provide feedback to the patients.
- Technological support is not provided during functional exercises because most of the available technological systems are not suited to support this type of exercises.[16] As there is growing consensus that exercises should be integrated into functional activities,[8] technological support should be available during these type of exercises.
- Technological support is lacking gaming aspects (e.g. fun or competition).[16] Up to 70% of patients with LBP do not adhere to exercise prescriptions,[44] which may lead to suboptimal treatment effects.[21,22] As serious games have to potential to improve motivation and adherence,[20,24,25] an important pathway for the improvement of treatment effects is currently unexploited.

In order to address the abovementioned shortcomings, this study assessed the feasibility of an exercise programme containing functional and home exercises, which were both supported by serious games. In addition, patients were offered a long term exercise programme (18 weeks). Patients with chronic low back pain (CLBP) typically need to continue exercising for a longer period,[11] while the motivating effects of SGs might decrease over time.[26] Therefore, we investigated whether serious games can be successfully integrated in a long-term rehabilitation programme.

3. What (materials)?

The ValedoMotion®system (version 1.2, Hocoma, Switzerland) was used to support the exercises with serious gaming. This system is a rehabilitation tool for patients with LBP, which consists of a laptop, remote control and three inertial wireless motion tracking sensors (40x30x16 mm, ±16 g). Two sensors are mounted to the patient’s spine at the L1 and S1 level (Fig. 1), while one sensor is used to calibrate the system. The sensor signals are sent to the laptop via which the patient can practise pelvic tilt exercises in a gaming environment (Fig. 2). The system uses the movements of the S1-sensor relative to the L1-sensor to control the games. In this way, patients have to dissociate lumbopelvic movements from the thoracic spine. Secondly, patients can receive feedback during functional motor control exercises (MCEs) using the ‘target game’ and the ‘coconut game’. The target game is displayed as a bull’s eye and the coconut game as a tray with coconuts (Fig. 3). The sensors detect the spinal movements and the cursor on the screen (target game) or the tray (coconut game) will move accordingly. When patients are able to control the lumbopelvic movements, they can keep the cursor in the middle of the bull’s eye or prevent the coconuts from falling off the tray.

Participants received an instruction manual containing information about how to use the Valedo®Motion system. In addition, they received a booklet containing pictures and a description of their (home) exercises.

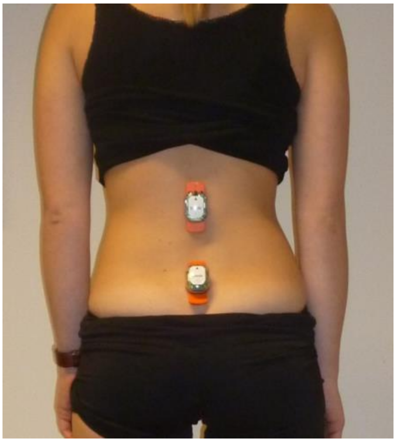

Fig. 1 Sensor Placement

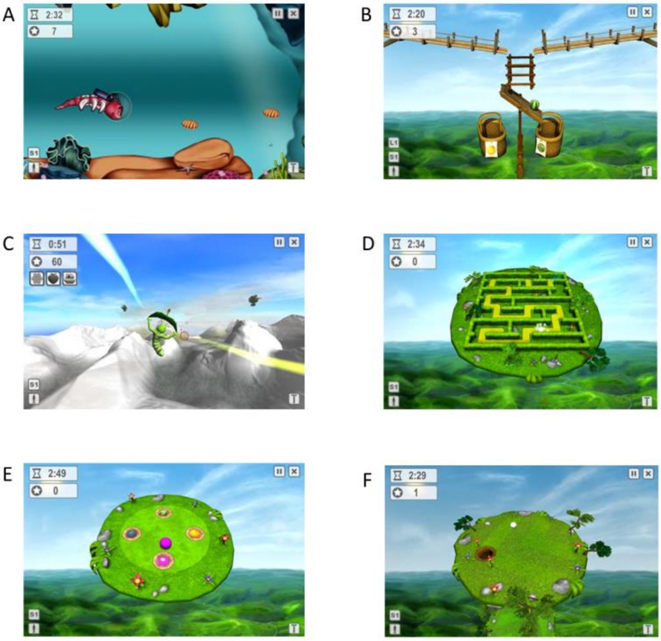

Fig 2 Serious games for pelvic control and thoracolumbar dissociation. **A**. Cavediver, for pelvic movements in the sagittal plane. **B**. Fruits, for pelvic movements in the frontal plane. **C-F**. Glider, Maze Square, Colours and Golf, for 3D pelvic movements.

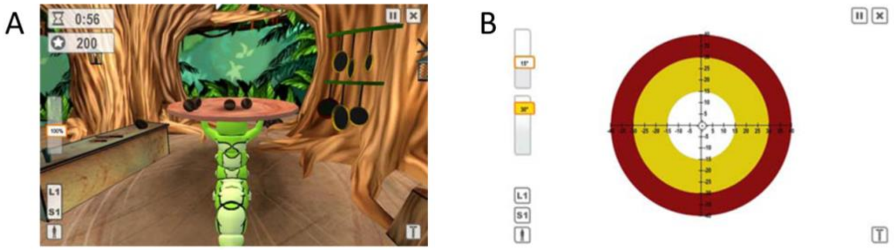

Fig 3 Serious games for postural feedback during functional motor control exercises. **A**. Coconut game. The difficulty of the game could be adjusted so that less lumbar movement was allowed before the coconuts fell off the tray. **B**. Target game.

4. What (Procedures)?

See parts 2 to 4 for a detailed description of the intervention and the rationale.

5. Who provided?

Participants performed the exercises under partial supervision of a physical therapist. All the physical therapists had at least five years of experience in treating patients with chronic low back pain. Prior to the study, all the therapists received a two hour education about the technological system.

6. How?

Participants performed the exercises under partial supervision of a physical therapist. Exercises without serious gaming were performed in a group of 6 to 10 patients in a gym. The exercises that were supported by serious games were performed individually in a separate room.

7. Where?

Subjects participated in an outpatient rehabilitation programme for low back pain (LBP) at a hospital. They were also asked to perform home exercises.

8. When and how much?

The intervention consisted of 36 sessions (two hours, twice weekly, 18 weeks in total). Each session consisted of 30 minutes of general reconditioning and 90 minutes of motor control exercises (MCE).

The general conditioning included cycling on a stationary bike at an intensity of 75% of the maximal heart rate, and exercises on a stepping machine and crosstrainer.

The MCE consisted of thoracolumbar dissociation exercises and functional MCE. During the sessions in the hospital, patients performed about 8 different MCEs (with variations, see case study). The number of repetitions of the MCEs was as follows:

- Thoracolumbar dissociation exercises
    - A total of 6 to 10 minutes
    - When these exercises were practised with the serious games, 5 games per session were played, each game lasting 2 minutes.
- Functional motor control exercises
    - Basis: when learning a new MCE:
        - No mental or physical fatigue was allowed
        - Three to five sets of 8 to 10 repetitions
    - Progression: when patients were familiar with the exercise:
        - Gradual progression to 3 sets of 20 repetitions
    - Further progressions and individual tailoring when patients were able to perform 3 sets of 20 repetitions:
        - Increase the number of repetitions (e.g. 3 sets of 30 repetitions) if patients needed to perform many repetitions of a certain task in daily life (e.g. job or sports).

  - Increase the load (e.g. handling heavier objects or adding resistance) – the number of repetitions could be lowered because of the increased load (e.g. 3 sets of 12 repetitions)
  - Increase the holding time for static positions (e.g. manual handling in a waiter's bow position)
  - Increase training variability (e.g. handling different objects, lifting from different heights)
  - Physical fatigue was allowed if patients needed to perform fatiguing tasks during daily life or sports.
  - Handling of real-life objects
  - Practise on unstable surfaces if necessary
  - Reduce and omit feedback (e.g. no tactile or visual feedback)

On the days that patients did not attend the sessions at the hospital, they were asked to perform home exercises:

- Thoracolumbar dissociation exercises
  - Six minutes per day in total, or three games of two minutes when using the serious games
- Functional motor control exercises
  - A selection of three exercises with the same number of repetitions as during the sessions in the hospital.

9. Tailoring

The motor control exercises were tailored to the patient's individual treatment goals. At the beginning of the intervention, patients were asked to formulate their treatment goals in consultation with the therapists. The achievement of the treatment goals was evaluated throughout the intervention. If an initial goal was reached, new objectives were agreed upon. Examples of treatments goals were: being able to clean the house, going for a mountain bike ride or being able to lift heavy boxes overhead. To achieve these goals, all the patients were treated according to the principles described below (see part 2 to 4 for details), but depending on their clinical presentation and individual treatment goals, different exercises were provided to each patient. An example is provided in Fig. 4 and in part 4 (case study).

10. Modifications

No modifications to the interventions were made.

11. How well?

The adherence towards the partially supervised sessions was measured by the number of attended treatment sessions in the hospital (range 1-36). Adherence to home exercises was evaluated with a diary, in which patients were asked to indicate how long they practised each day, and whether they used the serious games. Adherence to the hospital appointments was good (median = 36, interquartile range= 2.5). Because only three participants consistently filled in the home-exercise diary, no conclusions can be drawn regarding the adherence to home exercises. One participant dropped out after T1, due to personal reasons, which were not related to the study.

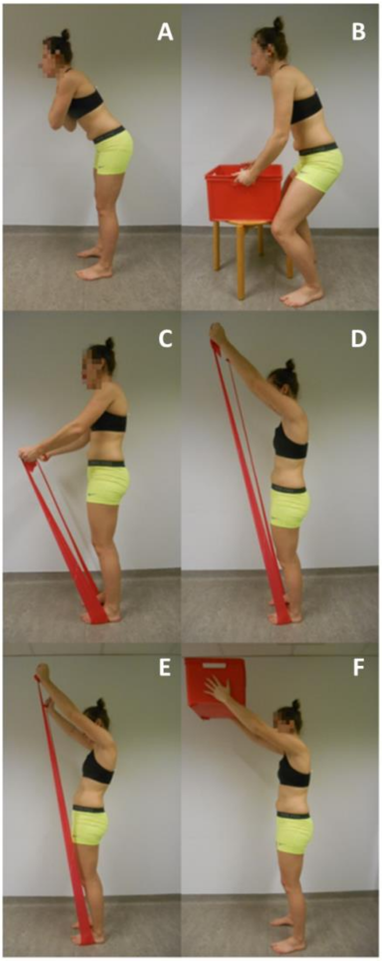

Fig 4 Functional motor control exercises. **A**. Waiter's bow: the patient is asked to bend forward in the hips while keeping the spine in a neutral alignment. **B**. Integration into a functional task: The patient is asked to lift the box with a neutral spinal alignment. The task is facilitated by placing the box on a chair. **C**. Functional exercises to prevent excessive lumbar extension during overhead lifting. The patient assumes a neutral spinal alignment. **D**. The patient lift the arms overhead with resistance from an elastic tube, while keeping the neutral spinal position. E. Incorrect performance with excessive lumbar extension. **F**. Integration of real-life objects: lifting a box overhead.

Part 2: Phases of the intervention and feedback scheme

2.1. Phases of the intervention

2.1.1 Week 1 – 3: Standard rehabilitation

Participants received a ‘standard rehabilitation’. This means that all exercises were performed without support by serious games. The decision not to support exercises immediately by serious games was made for various reasons:

- We wanted the patients to have a basic understanding of their exercises, before supporting them with serious games. When learning new and more complex exercises, providing too much external feedback can hinder the learning process. Instead of focusing on the own body movements (i.e. task-intrinsic feedback), the novice learner may focus too much on the extrinsic feedback and can become dependent on it, which in turn can hinder the learning process.[45]
- While serious games can be motivating, the opposite is true when the game challenge and player skills are not balanced.[17] When games are too hard, this can be frustrating and result in quick abandonment.[17] Patients with CLBP typically have a poor thoracolumbar dissociation, and some patients are completely unaware of how to perform pelvic tilts.[46] Although the difficulty level of the serious games could be adjusted, a basic understanding of how to control pelvic movements is necessary to play the games. We expected that these basic skills were lacking in the patients included in this study. Therefore, we believe it was necessary to first teach patients the basic skills to control the games before introducing them.

2.1.2 Week 4 – 5: Familiarisation with the serious games in the hospital

Patients received sensor-based postural feedback from the serious games during 45 minutes of motor control exercises in the hospital: 15 minutes of thoracolumbar dissociation exercises and 30 minutes of functional MCEs. The rest of the time, patients performed the motor control exercises without feedback from the serious games. Home exercises were not supported by serious games.

During the first session of week 4, participants received an explanation of the technological system by one of the physical therapists. First, the therapist demonstrated and explained how to set up the system and how to place the sensors on the spine. Immediately after this demonstration, participants were asked to set up the system themselves while being supervised by a therapist. During week four and five, patients became familiar with the serious games and the therapists checked whether the patients were able to set up and use the serious games correctly. By introducing a familiarisation period in the hospital, we wanted to avoid patients experiencing problems to use the technological system at home.

2.1.3 Week 6 – 13: Support by serious games at the hospital and at home

Both the motor control exercises in the hospital (see week 4 – 5) and the home exercises were supported by serious games.

2.1.4 Week 14 – 18: Standard rehabilitation

Patients received a standard rehabilitation, without support by serious gaming. By omitting the feedback form the serious games in the last weeks of the programme, we extended the concept of gradually reduced feedback (see paragraph 2.2).

2.2 Feedback scheme for functional motor control exercises

The feedback from the serious games during the motor control exercises was provided as follows: First, the patient was allowed to constantly look at the screen (concurrent feedback). If the exercise could be performed well, the patient was asked not to look at the screen during the exercise, but only after the exercise was completed (terminal feedback). In a next phase, the patient was asked to perform several repetitions before looking at the screen for feedback (fading feedback frequency). In this way, we wanted to improve the learning process and prevent patients becoming dependent on the feedback.[45] In addition, patients also performed the motor control exercises without support from the serious games. This is essential as patients should be able to control their lumbar spine movements during daily life activities when no extrinsic feedback is available.

Part 3: Detailed descripton of the intervention and rationale

The different steps are adapted from Hodges et aL (2013).[8]

Step 1: education

Patients were explained what a motor control problem is, and how it was related to their LBP. To explain the relation with LBP, we used the basic idea of the kinesiopathologic model.[47] A detailed description of this model can be found elsewhere.[47] In short, this model explains that repeated movements or sustained postures during daily life activities may lead to adaptations in the musculoskeletal system, such as changes in muscle stiffness and strength. This, in turn, can lead to alterations in movement patterns, where patients tend to move more at one region (e.g. lower lumbar spine) and less at adjacent regions (e.g. upper lumbar spine or hips). The repetition of these altered movement patterns can result in increased load on regional tissues and, eventually, to pain.

To resolve these problems, we should try to improve the control over the body area where the patients tends to move more (e.g. lumbar spine), and to increase the range of motion in an area where the patient is stiffer (e.g. hip or thoracic spine).[47] In this way, we try to alter the patient’s movement pattern in a way that less movement will occur at the painful site and in the painful movement direction, whereas this loss of movement will be compensated at a different body region. Clearly, this does not mean that patients are not allowed to move the lumbar spine (see step 4), but the goal is to reduce the end range movements into the painful direction, in order to reduce the amount of stress on the lumbar spine.[8]

Step 2: Pelvic tilts in different directions + postural correction

To control lumbar movements and posture, patients should be able to control their pelvis. By tilting the pelvis, the lumbar curvature can be adjusted.

Step 2.1 pelvic tilts

First, patients were taught pelvic tilts in the sagittal and frontal plane. Emphasis was placed on a correct dissociation between the lumbar and the thoracic spine (i.e. keep the thoracic spine still while moving the pelvis and lumbar spine). When patients were able to perform pelvic tilts in one movement plane, the exercises were made more difficult by using three dimensional pelvic tilts.

> Support by serious gaming:
>
> The games were played in a standing or sitting position, depending on the patients' needs. First, games requiring pelvic tilts in a single plane (sagittal or frontal) were used. Later, games requiring three dimensional pelvic tilts were introduced. Throughout the rehabilitation, the difficulty level of the games was increased. For example, patients had to avoid more objects (e.g. cavediver and golf game) or the game became more sensitive (i.e. more precise lumbar movement was necessary to control the games). The progress was based on the clinical evaluation by the physical therapists. By adjusting the level of difficulty to the patients' abilities, we aimed to improve the learning process and to balance the game challenge and player skills in order to keep patients motivated. By the end of the intervention, 13 different games were available for the patients.

Step 2.2 Postural correction.

Patients were taught how to place the spine in a more neutral alignment. A neutral alignment was considered to be a midrange position of the spine, usually a slight lumbar lordosis with a relaxed thorax.[48] Postural correction were made according to the patients' needs. For example, when a patient experienced pain with (prolonged) standing, emphasis was placed on correction the standing posture.

> Support by serious gaming:
>
> Postural correction was practised with the target game: First, the patient assumed the neutral spinal position and calibrated this position, placing the cursor in the middle of the bull's eye (Fig. 5A). The patient was then asked to relax so that the cursor moved away from the middle of the bull's eye (Fig. 5B), and to assume the neutral starting position again. If the exercise was performed correctly, the cursor was positioned back in the middle of the bull's eye after the repositioning.

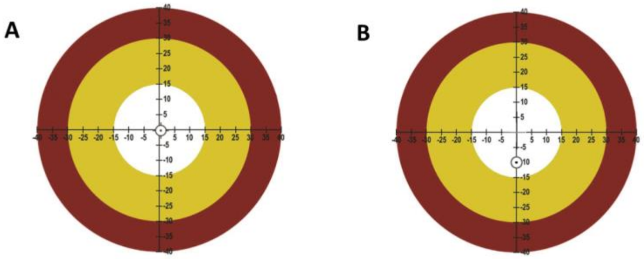

Fig. 5. A. The patient calibrates the system in the neutral position, placing the cursor in the middle of the bull's eye. **B**. When the patient relaxes and sits in a more slouched position (i.e. flexion of the spine), the cursor will move away from the middle of the bull's eye. When the patient assumes his neutral position again, the cursor should be in the middle of the bull's eye again, as shown in fig. A.

Step 3: retraining static stability + high level functional training

Patients learned how to keep their lumbar spine in a neutral position during a variety of exercises and functional movements (e.g. lifting a box from the floor). These movements were based on the patient history, physical examination and the patient's rehabilitation goals. If necessary, functional activities were first divided into more analytical movements (segmentation) and performance was made easier by training in unloaded positions and at slower speeds (simplification).[8] Analytical exercises were integrated into functional movements as soon as possible. The progression of exercises (e.g. number of repetitions) is described in part 1, point 8.

Support by serious gaming

Patients used the target game and the coconut game to receive feedback about their exercise performance (Fig. 3). After patients assumed their neutral position, they calibrated the system. Patients were instructed to keep the cursor in the middle of the bull's eye (target game), or to prevent he coconuts form falling off the tray (coconut game). When patients were not able to keep the lumbar spine in the neutral position, the cursor did not stay in the middle of the bull's eye (Fig. 5B). By tilting their pelvis, patients could adjust their lumbar curvature during the exercises.

Step 4: retraining dynamic stability + high level functional training

The same exercises and principles as in the static stability phase were used to retrain the dynamic stability. Instead of keeping the spine in the neutral position, the patient was instructed to move the lumbar spine in the previously painful direction, but with careful consideration not to allow exaggerated movement in the targeted segments. The progression of exercises (e.g. number of repetitions) is described in part 1, point 8.

Support by serious gaming

The support by serious games was similar to step 3. However, as lumbar movement was allowed, patients were asked to keep the cursor within the white area of the target game. The width of the white area of the target game, and the sensitivity of the tray (coconut game) was adjusted to match the allowed movement. When patients were not able to control their lumbar spine within the preset limits (bandwidth), the cursor moved outside the white circle of the target game, or the coconuts fell off the tray.

Part 4: Case study

4.1 Problem

A 56-year old man reported a history of 20 years of CLBP. The LBP had an insidious onset and progressively worsened over the years. He was a lorry driver who frequently had to load and unload boxes, weighing between 5 and 15kg. His most pain provoking movements were to lift and to stack boxes overhead during his job. The examination revealed motor control impairments towards extension and rotation. The main finding of the physical examination were as follows:

- Increased and uncontrolled movement towards extension at the lower lumbar spine, which was painful. This pattern was evident during analytical extension in standing, 3-dimensional extension and functional movements. As a functional movement, the patient was asked to perform the painful overhead lifting movement.
- Active rotation was painful at the lumbar spine, and restricted in the thoracic spine. The patient spontaneously moved slightly towards extension when asked to rotate his spine.
- Restricted thoracic extension and rotation.
- Difficulty with posterior pelvic tilts. The patient rather swayed the pelvis forward. The patient had poor thoracolumbar dissociation

A progressive exercise programme to address the specific problem of overhead lifting is described below.

Step 1: education

The kinesiopathologic model was explained. The patient was explained that the aim of the movement control exercises was reduce the extension and rotation movement in the lower lumbar spine, and increase the thoracic movement, as this would reduce the amount of stress on his lower lumbar spine.

Step 2: thoracolumbar dissociation exercises + postural correction

- Thoracolumbar dissociation exercises (i.e. pelvic tilts) were started in a standing position because this was the most functional position.
- Correction of the sway back position in stance.
- Technological support:
    - Pelvic tilts were practised in different directions with the serious gaming (Fig. 2). The games were mostly played in a standing position, as this was most relevant for the patient.
    - Postural correction was practised with the target game: the patient assumed his neutral spinal position and calibrated this position. He was then asked to relax, and to assume the neutral starting position again. If the exercise was performed correctly, the cursor was positioned back in the middle of the bull's eye after the repositioning (figs. 5A and 5B).

Step 3: retraining static stability + High level functional training

- *Basic exercise 1 (Figs. 4 C-F):* The patient was asked to assume his neutral spinal position and to lift the arms overhead (forward flexion in the sagittal plane). He was instructed only to go as far as he could maintain his neutral lumbar position. Attention was paid to a normal breathing pattern.
    - Progressions:
        - Lifting the arms higher
        - Increase of the load by using dumbbells and elastic bands
        - Overhead lifting of real-life objects (e.g. 5-15 kg boxes).

        - Increase of the number of repetitions of arm lifts, while constantly keeping the spine in the neutral position.
        - Increase the speed of movement
    - Modifications:
        - Instead of lifting the arms in the sagittal plane, the arms were lifted to a position of 135° of abduction, with external rotation (thumbs pointing backwards). Resistance to the arm movement was given with an elastic tube. In this way the patient also trained the interscapular muscles, which can help to improve his thoracic posture.
        - To introduce a rotational-component, the exercise was also performed with one hand.

- *Basic exercise 2 (Fig. 6 and Fig. 7):* The patient was asked to assume his neutral position while moving his arms back and forth in the horizontal plane. The patient was asked to maintain his neutral lumbar position, without rotating or extending the lumbar spine. Thoracic rotation or extension was allowed.
    - Progressions:
        - Both arms are moved from left to right (and vice versa) in the horizontal plane.
        - Movement of one arm in the horizontal plane against resistance from an elastic tube.
        - Movement of both arms in the horizontal plane against resistance from an elastic tube.
        - Movement of the whole body by pivoting around one foot. The arms are in the horizontal plane with resistance from an elastic tube.
        - Combine horizontal arm movements with whole body rotation.
        - The arms are moved in a 3D-direction, creating a rotation-extension force on the spine.

    - Progressions for increased resistance, speed and number of repetitions. Introduction of real-life and heavier objects, considering that the patient had to handle 5 to 15kg boxes.
- Technological support: The patient assumed and calibrated his neutral spinal position using the target and coconut game. He was asked to keep the cursor in the middle of the bull's eye, or to prevent the coconuts falling off the tray.

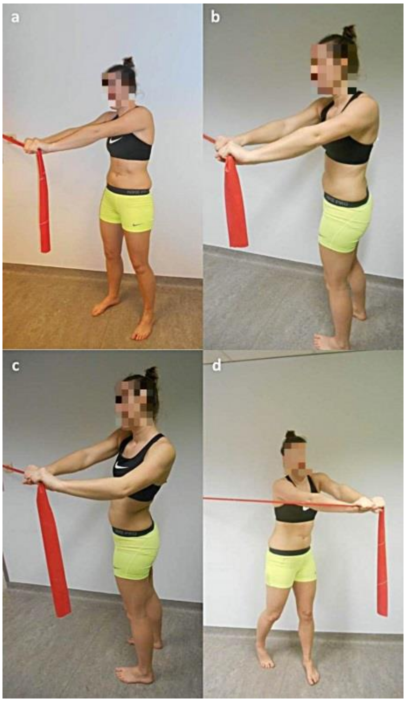

Fig. 6 Functional exercises to prevent excessive lumbar rotation. **a.** The patient assumes his starting position with a neutral spinal alignment. **b**. The patient moves the arms sideways against the resistance of an elastic tube and rotates the thoracic spine, while the lumbar spine remains in a neutral position. **c.** Incorrect performance with excessive lumbar extension and rotation. **d.** Integration of whole body rotation: the patient is asked to pivot around the left foot, while maintaining the neutral spinal position.

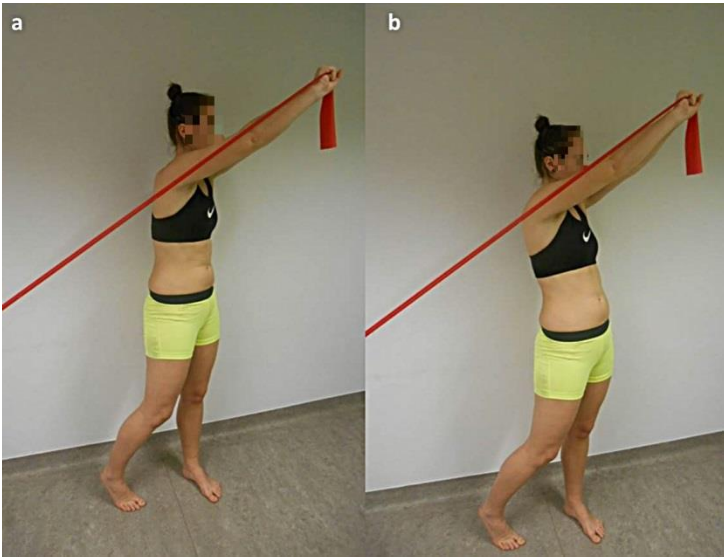

Fig. 7 Functional exercise to prevent excessive lumbar extension and rotation. **a**. Correct performance of a combined movement. **b**. Incorrect performance with excessive extension and rotation in the lumbar spine.

Step 4: Retraining dynamic stability + high level functional training

- *Adapted basic exercise 1*: The patient was asked to flex his lumbar spine by bringing his hands towards the floor. Then he was asked to return and to bring the arms overhead in a one fluent movement. In this way, the patient moves the lumbar spine from flexion into extension and introduces an extension moment by raising the arms overhead. However, the patient was instructed to prevent the lower lumbar spine from going into excessive lumbar extension, although some lumbar extension movement was allowed.
    - Progressions
        - Lift a box from a chair, and place it on an overhead shelf
        - Gradually lower the chair until the box is on the ground. Increase the height of the shelf.
        - Increase the weight of the box, movement speed, number of repetitions
- *Adapted basic exercise 2*: The same exercises as in the basic example, but lumbar spinal rotation was allowed. However, the patient focused on

increasing thoracic and hip rotation, while preventing the excessive lower lumbar extension and rotation.

- *Technological support*: The patient assumed and calibrated his neutral spinal position using the target game and coconut game. The cursor of the target game was allowed to move slightly towards extension and rotation (upwards and sideways, see fig. 8) or the tray was allowed to tilt slightly before the coconuts fell off.

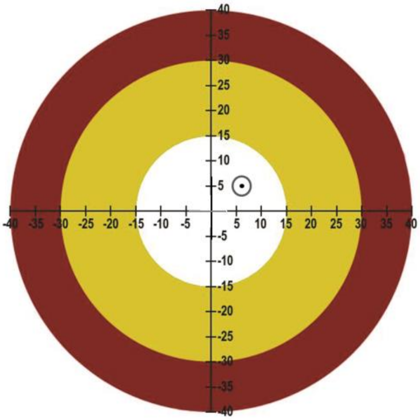

Fig. 8. Dynamic stability with target game. The cursor was allowed to move slightly away from the starting position.

Chapter II

Study 3

Within/between-session reliability and agreement of lumbopelvic kinematics in the sagittal plane during functional movement control tasks in healthy persons.

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Abstract

A lack of adequate lumbopelvic movement control has been suggested as an underlying mechanism contributing to the development and persistence of low back pain and lower limb pathologies. The purpose of this study was to assess the within and between session reliability (i.e. the ability to discriminate between subjects), and the agreement (i.e. whether scores are identical on repeated measures) of lumbopelvic kinematics in the sagittal plane during functional movement control tasks. Kinematics were measured with a portable inertial measurement unit system. Twenty healthy subjects (mean age= 22 (±3.6) years, 15 females) performed four tasks on two occasions, five to seven days apart: waiter's bow (WB), lifting a box from the floor (LIFT), stance-to-sit-to-stance (SIT) and placing a box on an overhead shelf (OVERH). Participants were asked to keep the lumbar spine in a neutral lordosis during the tasks. The maximal deviations from the neutral starting position for the lumbar spine and hip were calculated. Intraclass correlations (ICCs), standard errors of measurement (SEM), minimal detectable changes and 95% limits of agreement were used to assess reliability and agreement. WB and LIFT were substantially reliable (ICC= 0.89-0.93), SIT was moderately to substantially reliable (ICC= 0.69-0.92) and OVERH was fairly to moderately reliable (ICC= 0.40-0.67). SEMs ranged between 1.1° and 3.1° for the lumbar spine and between 0.7° and 4.8° for the hip. Based on the substantial reliability and acceptable agreement, WB and LIFT are most appropriate to quantify lumbopelvic movement control during functional tasks.

1 Introduction

A lack of adequate lumbopelvic movement control (MC) has been described in various populations, such as patients with low back pain[1] and lower limb pathologies.[2,3] Although the relationships have yet to be clarified, it is suggested that inadequate lumbopelvic MC may be an underlying mechanism contributing to the persistence of pain and suboptimal functioning.[1] Therefore, it is essential to evaluate these aspects in the assessment of these patients.[4]

Lumbopelvic MC is typically being assessed by observation because this is an inexpensive and fast way of examining a patient. However, this method mostly uses a dichotomous outcome (correct/incorrect performance), which does not allow to quantify the performance on the test.[5] Kinematic measurements recorded with clinical (e.g. inertial sensors) or lab based (e.g. stereophotogrammetric) systems can be used to quantify aspects of lumbopelvic MC. However, such measurements are only of clinical and research value if kinematics can be obtained reliably and with sufficient agreement.

Studies investigating the reliability and agreement of lumbopelvic kinematics of MC tasks are scarce.[6,7] Moreover, only analytical MC tests have been described in these papers. This is a major shortcoming since it is recommended to include functional MC tasks into the physical examination of patients with MC problems.[8] These tasks may better identify aberrant movement patterns contributing to the patient’s problem, as they assess the ability to control lumbopelvic movements during daily life activities, whereas analytical MC tests use movements not directly related to daily life (e.g. tests in prone lying) .

The first aim of this study is to assess in healthy persons the within-session and between-session reliability of lumbopelvic kinematics in the sagittal plane during functional MC tasks, using wireless inertial measurement sensors. Secondly, the agreement and minimal detectable change between two sessions will be investigated.

2 Methods

2.1 Study design and population

This within -and between-session reliability study with agreement was conducted according to the GRRAS-guidelines.[9] Healthy subjects between 18 and 65 years old were recruited at the campus of Hasselt University, Belgium. Based on the number of repetitions in our protocol, 18.4 subjects allow reliability estimations of ICCs >0.9 (H1) with a type I error of 0.05, type II error of 0.20 and minimally acceptable ICC-value of 0.7 (H0). Because data might get lost because of technical problems (e.g. signal loss from sensors), 20 subjects were included using consecutive sampling.[10] Subjects were excluded if they had low back pain in the past year, previous spinal surgery, a serious underlying pathology, physical impairments interfering with daily functioning or if they performed spinal MC exercises in the past year. The study was approved by the Ethical Committee of Hasselt University and the Jessa Hospital, Belgium (B243201423040). All subjects gave written informed consent before being included in the study.

2.2 Measurement procedure

Subjects were tested on two occasions at the same time of the day, five to seven days apart. They were asked not to practise the lumbopelvic MC tasks between the two test occasions or to perform strenuous activities at the day or the day before the testings. All measurements were performed by the same researcher (T.M.) who has 12 years of experience in lumbopelvic MC assessment.

Four different MC tasks were assessed: waiter’s bow (WB), stance-to-sit-to-stance (SIT), lifting a box from the floor (LIFT) and placing a box on an overhead shelf (OVERH) (Figs. 1 A-D). A detailed description of the tasks is provided in Appendix A. Each task started from a standing position, with the lumbar spine placed in a neutral lordosis. To find the neutral lordosis, the total range of pelvic motion was evaluated, after which the lumbar spine was placed in a midway position. Subjects were asked to maintain their neutral lumbar curvature while performing the tasks. Before the measurements, all tasks were explained and demonstrated in a standardized way, and subjects could practise these tasks until they felt familiar with it. During the actual assessment, each task was performed five times at a self-selected speed. All repetitions of a specific task were performed immediately after each other, while there was a resting period of three minutes between the different tasks. Before each repetition, subjects were placed in the neutral position by a research assistant. Real-time kinematic feedback was available for the researchers to ensure that subjects were placed in the same neutral position before each repetition. When the habitual standing position of a subject corresponded with a neutral position, no postural correction was made before the tests. No feedback was given to the participants during the assessment-trials. To avoid systematic learning effects, the task order was randomized for both test occasions. Each task was standardized for the subject's height (Appendix A).

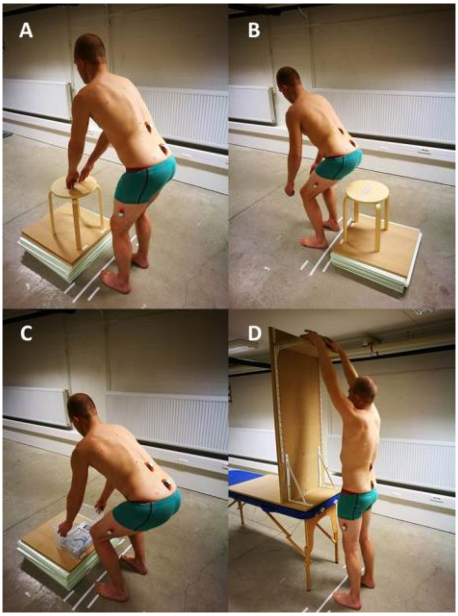

Fig. 1 Functional movement control tasks. A: Waiter's bow. B: Stance-to-sit-to-stance. C: Lifting a box from the floor. D: Placing a box on an overhead shelf.

2.3 Kinematic data acquisition

The Valedo®motion research tool (Version 1.2, Hocoma, Switzerland) was used to assess the sagittal plane lumbopelvic kinematics. The Valedo®motion consists of three wireless inertial measurement sensors that contain a triaxial magnetometer, gyroscope and accelerometer, and measures with an accuracy of 0.1 degrees and a sampling rate of 50H. This instrument has a proven concurrent validity to measure lumbopelvic movements in the primary movement planes.[7] The sensors were placed on the spinous process of L1 and S1, and 20 cm above the lateral femoral condyle. Before the measurements, the sensors were calibrated to the magnetic north and the sagittal plane was defined. The latter was done by calibrating an additional sensor while it was placed in a specifically designed holder which was held exactly parallel with the tape on the floor. The angles were derived from quaternions using the tilt/twist method. This method is preferred over the Euler/Cardan method, because no specific order of rotations around movement axes is required for the calculation of joint angles and because tilt/twist angles only reach singularity at 180°.[11]

2.4 Outcome parameters

For each repetition, the maximal deviation from the starting position was calculated and expressed in absolute values. Lumbar spine angles were calculated from the L1-sensor relative to the S1-sensor, while hip angles were calculated from the S1-sensor relative to the femoral sensor.

2.5 Statistical analysis

Statistical analysis was performed with SPSS, version 22 (Chicago, IL) and R, version 3.3.2. Because the Shapiro-Wilk test indicated that data were normally distributed, means and standard deviations (SDs) for all outcome parameters were calculated. Reliability was calculated using the intraclass correlation coefficient (ICC), with a 95% confidence interval (95%CI). Single data from the first test occasion were used for the within-session reliability ($ICC_w(2,1)$), while average data from both test occasions were used for the between-session reliability ($ICC_b(2,k)$). ICCs were interpreted according to Shrout[12]: values >.80 represent substantial, 0.61-0.80 moderate, 0.41-0.60 fair, 0.11-0.40 slight and 0-0.10 virtually no reliability. A negative lower limit for a 95%CI was set to zero.[13]

The standard error of measurement (SEM) was obtained to assess agreement. The SEM was calculated as follows: $SEM = SD*\sqrt{(1-ICC)}$.[14] A proportional SEM (%SEM) was obtained by expressing the SEM relative to the mean (%SEM= (SEM/mean)*100). The minimal detectable change (MDC) between two sessions was calculated using $SEM_b*1.96*\sqrt{2}$.[15] The proportional MDC (%MDC) was calculated by expressing the MDC relative to the $mean_b$ (%MDC= $(MDC/mean_b)*100$), where the $mean_b$ was obtained as follows: ((mean session 1 + mean session 2)/2).

Bland & Altman plots were created to display the individual subject differences between the tests against the respective individual means. The means of the differences ($means_{diff}$) between the tests and their SDs (SD_{diff}) were calculated. The 95% limits of agreement (LOAs) were obtained with the following formula: $mean_{diff} \pm 1.96*SD_{diff}$. Because the differences were normally distributed, a one sample t-test using the $means_{diff}$ was used to check for systematic bias between test and retest. Heteroscedasticity was examined by observation of the graphs and a Pearson correlation coefficient.[16]

3 Results

Twenty one participants volunteered and were screened. One subject experienced low back pain on the day before the first session and was excluded. Finally, fifteen females and five males were included. The mean (±SD) age was 22 (±3.6) years, height 172.4 (±6.8) cm, weight 65.7 (±8.7) kg and BMI 22.1 (±2.5) kg/m². The habitual standing position of four subjects corresponded with a neutral lordosis of the lumbar spine.

3.1 Reliability and agreement

ICCs are presented in Table 1. Means (±SD) and agreement parameters for the within- and between-session measurements can be found in Table 2 and 3 respectively.

3.1.1 Lumbar spine

$ICCs_w$ and $ICCs_b$ showed substantial reliability for WB and LIFT (ICC= 0.89–0.93), while SIT and OVERH were fairly to moderately reliable (ICC= 0.56-0.77). For all the tasks, $SEMs_w$ and $SEMs_b$ ranged between 1.1°-3.1°, corresponding with MDCs of 2.9°-8.5°. For WB, LIFT and SIT, this resulted in %SEMs ranging between 12.1%-17.6% and MDCs between 33.6%- 48.7%. %SEMs and %MDC for OVERH were consistently larger.

3.1.2 Hip

Both within- and between-session reliability was substantial for WB, LIFT and SIT (ICC= 0.89–0.96), except for ICC_b for SIT (ICC= 0.78). OVERH was slightly to fairly reliable (ICC= 0.40-0.43). For all the tasks, SEMs ranged between 0.7°-4.8°, resulting in MDCs between 1.9°-13.3°. For WB, SIT and LIFT, %SEMs and %MDCs varied between 3.5%-11.8%, and between 9.6%-32.7% respectively. For OVERH, %SEMs and %MDC were consistently larger.

3.1.3 Bland & Altman plots and limits of agreement

The mean differences between test occasions and LOAs are presented in Table 3. There were no significant differences between mean scores on the test and retest. No heteroscedasticity was present, except for LIFT of the lumbar spine ($\rho = 0.57$, $p < 0.01$). Bland & Altman plots are provided in Appendix B.

Table 1 Intraclass correlation coefficients for within –and between-session reliability.

Task	ICCw (95% CI)	*p*-value	ICCb (95% CI)	*p*-value
Lumbar spine				
WB	0.92 (0.85, 0.96)	<0.01	0.89 (0.73, 0.96)	<0.01
LIFT	0.90 (0.82, 0.95)	<0.01	0.93 (0.82, 0.97)	<0.01
SIT	0.77 (0.62, 0.88)	<0.01	0.69 (0.18, 0.87)	0.01
OVERH	0.67 (0.49, 0.83)	<0.01	0.56 (0.00, 0.83)	0.05
Hip joint				
WB	0.96 (0.93, 0.98)	<0.01	0.89 (0.72, 0.96)	<0.01
LIFT	0.91 (0.83, 0.96)	<0.01	0.91 (0.77, 0.97)	<0.01
SIT	0.92 (0.86, 0.97)	<0.01	0.78 (0.43, 0.91)	<0.01
OVERH	0.43 (0.23, 0.66)	<0.01	0.40 (0.00, 0.74)	0.10

95% CI= 95% confidence interval; ICCb= intraclass correlation coefficient between sessions; ICCw= intraclass correlation coefficient within sessions, LIFT= lifting task, OVERH= overhead task; SB= standing bow task, SIT= stance-to-sit-to-stance task.

Table 2 Within-session means, standard deviations, and standard error of measurements

Task	Lumbar spine				Hip			
	Mean (°)	SD (°)	SEMw (°)	SEMw %	Mean (°)	SD (°)	SEMw (°)	SEMw %
WB	16.0	7.9	2.2	13.8	35.2	14.9	3.0	8.4
LIFT	15.2	7.3	2.3	15.2	90.4	11.5	3.5	3.8
SIT	17.3	4.9	2.3	13.6	83.3	11.9	3.4	4.0
OVERH	4.5	2.1	1.2	26.6	2.3	0.9	0.7	29.3

%SEM$_w$= (SEM$_w$/Mean), LIFT= Lifting task, Mean= Mean maximal deviation from the starting position, OVERH= Overhead task, SB= Standing bow task, SD= Standard deviation, SEMw= Standard error of measurement within-session, SIT= Stance-to-sit-to-stance task

Table 3 Between sessions means, standard deviations, standard error of measurements, minimal detectable changes and 95% limits of agreement

Task	Mean$_b$ (°)	SD$_b$ (°)	SEMb (°)	%SEMb	MDC (°)	%MDC	Mean$_{Diff}$ (°)	SD$_{Diff}$ (°)	*p*-value	LOA (°)
Lumbar spine										
WB	15.3	7.1	2.3	15.3	6.5	42.5	1.4	3.9	0.14	-6.2, 8.9
LIFT	15.7	7.2	1.9	12.1	5.3	33.6	-1.0	3.8	0.26	-8.3, 6.4
SIT	17.4	5.5	3.1	17.6	8.5	48.7	-0.1	5.6	0.91	-11.0, 10.7
OVERH	4.4	1.6	1.1	24.0	2.9	66.3	0.2	1.6	0.51	-2.9, 3.3
Hip joint										
WB	35.7	12.7	4.2	11.8	11.7	32.7	-1.0	8.2	0.59	-17.0, 15.0
LIFT	91.6	10.6	3.2	3.5	8.8	9.6	-2.3	6.1	0.13	-14.2, 9.8
SIT	82.7	10.2	4.8	5.8	13.3	16.0	1.2	6.8	0.44	-12.1, 14.4
OVERH	2.6	0.9	0.7	26.7	1.9	74.1	-0.4	0.9	0.06	-2.1, 1.3

%MDC= (MDC/Mean$_b$), %SEM$_b$= (SEM$_b$/Mean$_b$), LIFT= Lifting task, LOA= Bland & Altman 95% limits of agreement, MDC= Minimal detectable change, Mean$_b$= Mean maximal deviation from the starting position, Mean$_{Diff}$: mean of the differences between test and retest, OVERH= Overhead task, WB= Waiter's bow task, SD= Standard deviation, SEMb= Standard error of measurement between-sessions, SIT= Stance-to-sit-to-stance task. The *p*-value is for the one-sample t-test for the Mean$_{diff}$.

4 Discussion

The within- and between-session reliability of WB, LIFT and SIT were moderate to substantial (ICC= 0.69–0.96). This is in line with results from other studies investigating the reliability of lumbopelvic kinematics measured with various systems during analytical,[17,18] and functional tasks.[19,20] In contrast to the present study, participants in previous studies were asked to perform the tasks in a habitual way. Because these are familiar movements, it might be expected that subjects were able to perform the tasks in a more consistent way compared to the unfamiliar and newly learned tasks in the current study.[21] However, the fact that the ICCs in the current study were similar to those reported in the aforementioned studies might be explained by the thorough standardization and short familiarization period before the start of the assessment.

ICCs for OVERH were clearly lower (range= 0.40-0.67), which can be attributed to the small movement range and the lower between-subject variance. These results confirm the findings of Bauer et al.,[6] who showed that analytical lumbopelvic MC tasks with smaller movement ranges are less reliable.[6]

In contrast to the ICCs, the absolute values of the agreement parameters (SEM, MDC and LOA) for OVERH were better than for the other tasks. However, relative to their means, they indicate less agreement. Consequently, little improvement in MC is needed to exceed the measurement error in absolute values (MDC lumbar spine= 2.9°), but the opposite is true for the relative values (%MDC lumbar spine= 66%).

The lumbar spine MDCs (≈5-6°) and %MDCs (≈30-40%) for WB and LIFT might be appropriate for clinical use. However, lumbar kinematics were measured using sensors at the L1 and S1 level, which means that the lumbar spine was regarded as one segment. While changes smaller than 5° might not be clinically important regarding to the total lumbar range of motion, differences of this magnitude might be relevant for patients who display aberrant movement patterns at a segmental level. Furthermore, patients with a lack of MC at the lower lumbar spine might try to correct their movement pattern at the thoracolumbar region.[8] Consequently, kinematic data solely obtained from L1 and S1 movements may not be able to detect these patterns. Therefore, future research should focus on the reliability and agreement of kinematic measurements of different segments of the spine during functional MC tasks. Finally, kinematics can only measure certain aspects of MC. Other parameters, such as muscle activation patterns, are also important to consider in MC assessment.[8]

Notwithstanding its limitations, this study can help to quantify lumbopelvic MC during WB, LIFT, SIT and OVERH tasks. In addition, the use of portable wireless inertial sensors increases the feasibility for kinematic assessments in a clinical setting.

5 Conclusions

WB and LIFT showed substantial within –and between-session reliability, SIT was moderately to substantially reliable, while OVERH was fairly to moderately reliable. Based on the substantial reliability and acceptable agreement, WB and LIFT are most appropriate for the assessment of lumbopelvic MC during functional tasks. Future research should focus on more localized kinematics at the lumbar spine and MC tasks in other movement planes.

Acknowledgements

We would like to thank Dr. Francesca Solmi for her advice on the data analysis.

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Appendix A: Detailed task descriptions

Waiter's Bow (WB)

Subjects stood with slightly flexed knees (i.e. no hyperextension) and were asked to bend in the hips, while maintaining their lumbar spinal curvature. Participants had to touch the middle of a stool, marked with a piece of tape, that was placed 15 cm in front of the hallux, and to return to their starting position. The height of the stool was standardized at 10 cm above the base of the patella (Fig. 1A).

Stance-to-sit-to-stance (SIT)

A chair without arm and back support was positioned 10 cm behind the calcaneus of the subject. The top of the chair was placed 5cm above the base of the patella. Subjects were instructed to sit down, remain seated for one second and stand up from the chair while maintaining their lumbar spinal curvature. The arms were by the subjects' side and it was not allowed to take support with the hands on the knees, or to initiate the sit-to-stance phase with an arm swing (Fig. 1B).

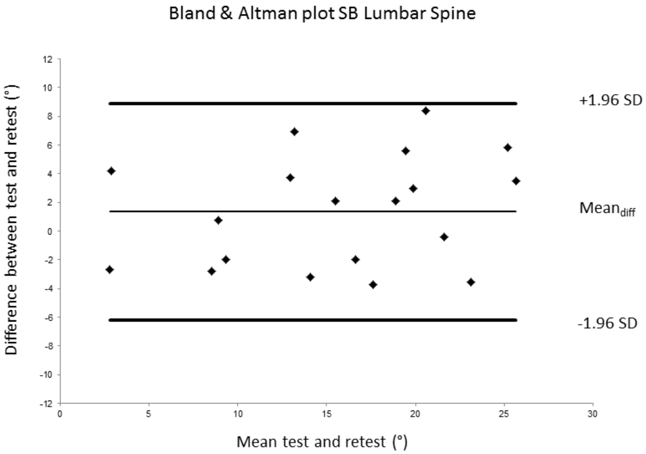
Lifting a box from the floor (LIFT)

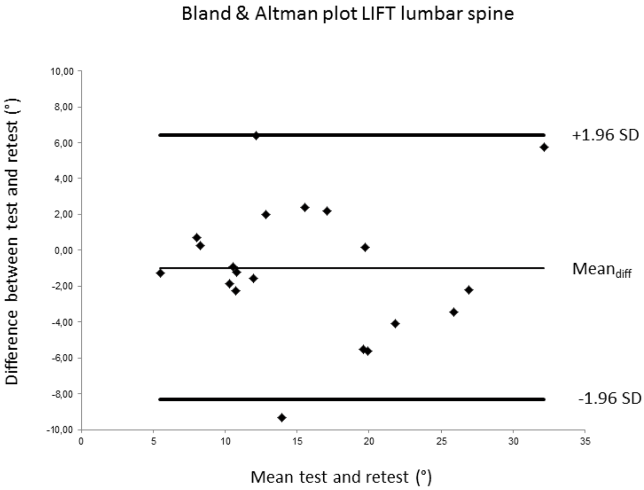
Subjects were asked to lift a box with handles from the floor while maintaining their lumbar spinal curvature, and to put it down again in the same way. Before putting the box on the ground, the participants were instructed to remain in a standing position for one second. The top of the box was positioned 10 cm below the apex of the subjects' patella. The dimensions of the box were 40x30x23.5 cm, and it weighed 3 kg (Fig. 1C).

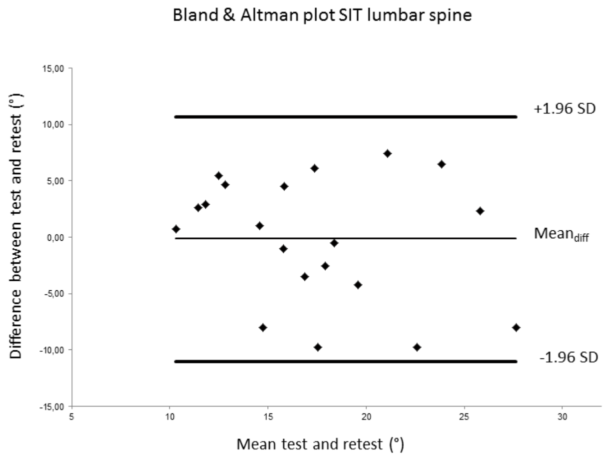
Placing a box on an overhead shelf (OVERH)

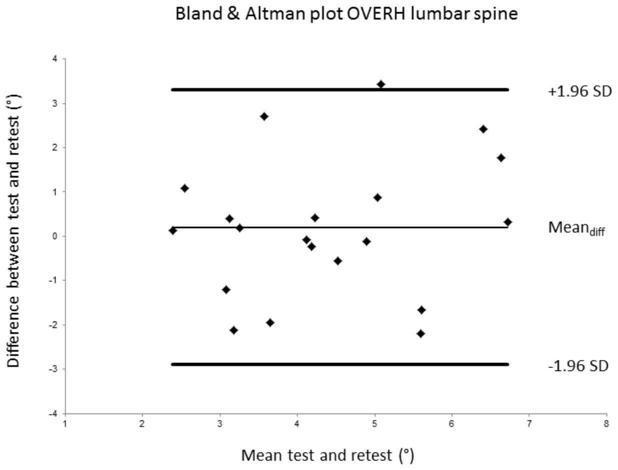
Subjects stood in front of a table and were asked to place a box (20x17x8 cm) weighing 2kg on a shelf while maintaining their lumbar spinal curvature. The height of the shelf was adjusted so that it was level with the subjects’ ulnar styloid process when the arms were in the maximal overhead position. After placing the box on the shelf, participants were asked to lower the arms to the starting position, remain in this position for one second, and to pick the box from the shelf and to put it on the table again (Fig. 1D).

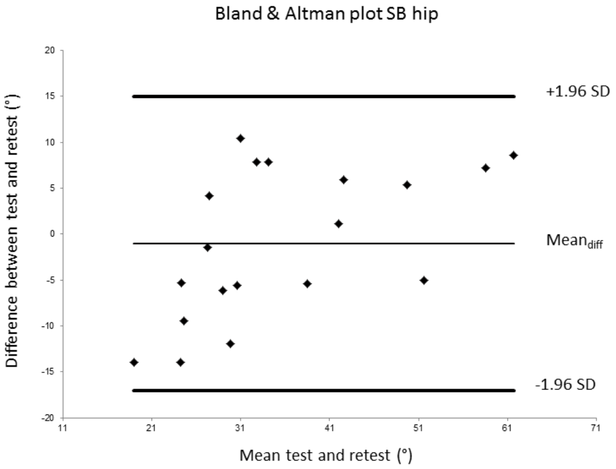
Appendix B – Bland & Altman plots

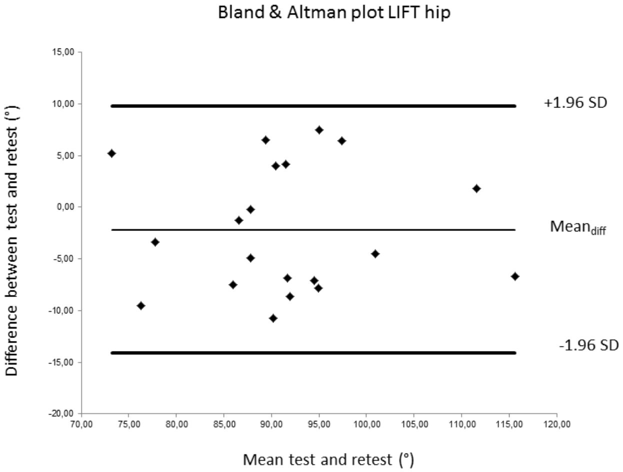


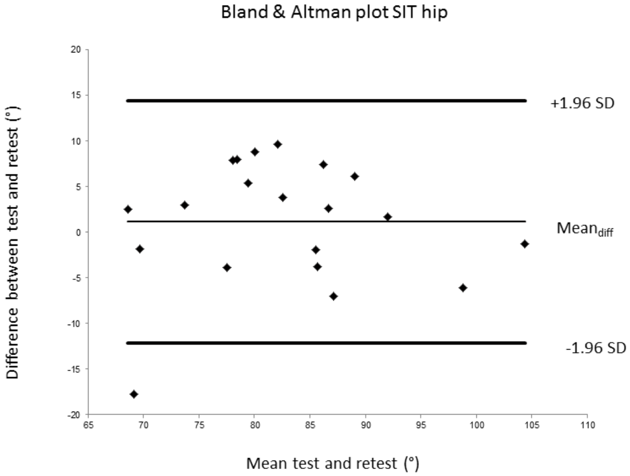



Bland & Altman plot SIT lumbar spine


Bland & Altman plot OVERH lumbar spine


Bland & Altman plot SB hip


Bland & Altman plot LIFT hip


Bland & Altman plot SIT hip
Difference between test and retest (°)
Mean test and retest (°)
+1.96 SD
Mean$_{diff}$
-1.96 SD
20
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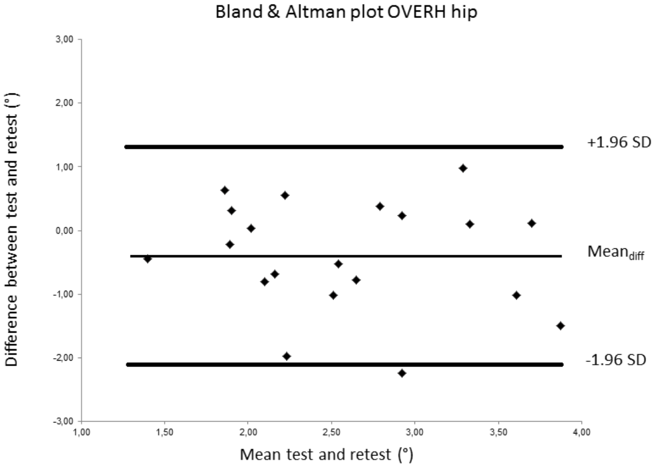
Bland & Altman plot OVERH hip
Difference between test and retest (°)
Mean test and retest (°)
+1.96 SD
Mean$_{diff}$
-1.96 SD
3,00
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Study 4

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.

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Abstract

Background: Improving movement control can be an important treatment goal for patients with chronic low back pain (CLBP). Although external feedback is essential when learning new movement skills, many aspects of feedback provision in patients with CLBP remain currently unexplored. New rehabilitation technologies, such as movement sensors, are able to provide reliable and accurate feedback. As such, they might be more effective than conventional feedback for improving movement control. The aims of this study were (1) to assess whether sensor-based feedback is more effective to improve lumbopelvic movement control compared to feedback from a mirror or no feedback in patients with chronic low back pain (CLBP), and (2) to evaluate whether patients with CLBP are equally capable of improving lumbopelvic movement control compared to healthy persons.

Methods: Fifty-four healthy participants and 54 patients with chronic non-specific LBP were recruited. Both participant groups were randomised into three subgroups. During a single exercise session, subgroups practised a lumbopelvic movement control task while receiving a different type of feedback, i.e. feedback from movement sensors, from a mirror or no feedback (=control group). Kinematic measurements of the lumbar spine and hip were obtained at baseline, during and immediately after the intervention to evaluate the improvements in movement control on the practised task (assessment of performance) and on a transfer task (assessment of motor learning).

Results: Sensor-based feedback was more effective than feedback from a mirror ($p < 0.0001$) and no feedback ($p < 0.0001$) to improve lumbopelvic movement control performance (Sensor vs. Mirror estimated difference 9.9° (95% CI 6.1°-13.7°), Sensor vs. Control estimated difference 10.6° (95% CI 6.8°-14.3°)) and motor learning (Sensor vs. Mirror estimated difference 7.2° (95% CI 3.8°-10.6°), Sensor vs. Control estimated difference 6.9° (95% CI 3.5°-10.2°)). Patients with CLBP were equally capable of improving lumbopelvic movement control compared to healthy persons.

Conclusions: Sensor-based feedback is an effective means to improve lumbopelvic movement control in patients with CLBP. Future research should

focus on the long-term retention effects of sensor-based feedback.

Trial registration: clinicaltrials.gov NCT02773160

1 Background

The lifetime prevalence of low back pain (LBP) is reported to be as high as 84%, whereas the estimated prevalence of chronic LBP (CLBP) is approximately 23%.[1] Globally, it is the leading cause of disability[2] and one of the most important reasons for work absenteeism, resulting in a high socioeconomic burden.[3]

Patients with CLBP form a heterogeneous group, which is exemplified by the differences in movement patterns within this population. While some patients with CLBP stiffen their spine and avoid spinal movements, others show the opposite pattern and adopt end range postures or move excessively into their painful direction.[4] For the latter type of patients, movement control exercises are often prescribed.[5] The aim of these exercises is to learn how to control movements into the painful direction, thereby reducing the mechanical load on the painful structures and decreasing peripheral nociceptive input.[6]

Changing movement patterns requires motor learning. The importance of external feedback (i.e. feedback coming from a source external to the person performing the task[7]) in motor learning has been well established, and optimizing the way feedback is provided is therefore essential.[8,9] While there is an abundance of literature on the role of extrinsic feedback to improve motor learning in a healthy population, many aspects of feedback provision in patients with LBP remain currently unexplored.[9] When patients with LBP perform lumbar movement control exercises in the absence of a therapist, they typically have to rely on visual feedback (e.g. from a mirror) or palpation.[10] However, the reliability and accuracy of these types of feedback can be questioned,[11,12] which may lead to a suboptimal learning process.[7] With the development of rehabilitation technologies, new opportunities for providing external feedback have emerged.[13] For example, wireless inertial motion sensors can be used to provide easy to understand and accurate feedback to the patient (e.g. via an avatar).[13,14] As such, sensor-based postural feedback might be more effective than conventional feedback for improving movement control, which in turn may enhance treatment effects.

Although movement control exercises are widely used in a variety of chronic pain populations, little is known about the influence of chronic pain on the capacity to learn new movement skills. From a theoretical perspective, it has been suggested that patients with CLBP might have a reduced motor learning capacity.[15] One of the reasons for this hypothesis is that LBP can negatively influence proprioceptive acuity, leading to impaired intrinsic feedback from the lumbar spine[16] As a consequence, patients with LBP might have to rely more on external feedback and become more dependent on it.[7] In addition, pain demands attention and can distract patients from the movement task,[17] which might in turn interfere with the learning process[15] However, empirical evidence for a reduced motor learning capacity in patients with CLBP is currently lacking and the scantly available research in other chronic pain populations shows equivocal results.[18,19]

Therefore, the aims of this study were (1) to assess whether sensor-based feedback is more effective to improve lumbopelvic movement control compared to feedback from a mirror or no feedback in patients with chronic low back pain (CLBP), and (2) to evaluate whether patients with CLBP are equally capable of improving lumbopelvic movement control compared to healthy persons.

2 Methods

2.1 Design

A randomised controlled trial including healthy persons and patients with CLBP was conducted. Both groups of participants were randomised into three subgroups, each receiving a different type of feedback during the intervention, i.e. feedback from sensors, a mirror or no feedback (= control group). Randomisation was done with a computerised random sequence generator and allocation concealment was obtained by using sequentially numbered, sealed, opaque envelopes prepared by a person not further involved in the study.

The intervention consisted of a single exercise session during which participants practised a movement control task while receiving their assigned type of feedback. Movement control was assessed with lumbopelvic kinematics, which were obtained at baseline, during and immediately after the intervention.

2.2 Participants

Participants were recruited at private physiotherapy and GP practices and via social media. To be included, all participants needed to be between 18 and 65 years old and patients had to be diagnosed with chronic non-specific LBP (>3 months, ≥3 days/week). Exclusion criteria for all participants were: spinal surgery in the past, an underlying serious disease or a physical problem interfering with daily life activities (e.g. severe knee pain), signs or symptoms of nerve root involvement, performance of lumbopelvic movement control exercises in the past year and pregnancy. Healthy subjects were also excluded if they experienced LBP in the past year.

To ensure that participants were able to achieve an improvement in movement control, the performance on the baseline movement control tasks was an additional inclusion criterion. To be included, the maximal lumbar range of motion during the baseline movement control tasks had to exceed 10° (0° would be a perfect performance). Participants with less range of motion on either of the baseline movement control tasks were excluded. Although this threshold of 10° was set a priori, the lumbar range of motion could only be calculated after completion of the full protocol. Therefore, all of the included participants completed the protocol, but only those fulfilling the abovementioned criterion were included in the final analysis.

2.3 Assessments

2.3.1 Baseline assessments

Sociodemographic data were obtained from all participants. Patients with CLBP also completed the Numeric pain rating scale (NPRS)[20] to assess current pain and the average pain during the past 7 days, the Roland Morris Disability questionnaire (RMDQ)[21] to assess disability and the Tampa scale for kinesiophobia[22] to assess the fear of movement/re-injury due to physical activity. After completing the questionnaires, participants performed two movement control tasks, i.e. a lifting task followed by a waiter's bow (Fig. 1). Both tasks were standardised for the participants' height and assessed with lumbopelvic kinematic measurements in the sagittal plane. Before the baseline kinematic measurements, the tasks were explained and demonstrated in a standardised way. For the lifting task, participants started from a relaxed standing position and were asked to lift a box with handles from a platform on the floor and to put it back down, while maintaining their lumbar curvature (i.e. not to flex or extend the lumbar spine). Participants were allowed to flex their knees as far as they wanted to. The distance from the box to the hallux was 15 cm. The dimensions of the box were 40 x 30 x 23.5 cm, and it weighed 4 kg. The top of the box was positioned 10 cm below the apex of the subjects' patella. For the waiter's bow, participants started with slightly flexed knees (±20°). Participants were instructed to keep their knees in the same position and to bend forward in the hips while maintaining their lumbar curvature. Participants had to touch the middle of a stool, marked with a piece of tape, which was positioned 15 cm in front of the hallux, and to return to their starting position. No familiarisation was allowed, and each task was performed five times at a self-selected speed.

2.3.2 Assessments during and after the intervention

Kinematics were also obtained during and three minutes after the intervention. For the post-intervention kinematic assessment, participants first performed the waiter's bow and then the lifting task as described above. Immediately after the post-intervention kinematic assessment, all participants were asked to complete the Borg-scale for perceived exertion.[23] and to answer two questions on a 0 to 10 numeric rating scale: 'what was your average LBP intensity during the experiment?' (0= no pain at all, 10= worst imaginable pain), 'how fearful were you to damage your back?' (0= not fearful at all, 10= extremely fearful). If significant between group differences would be present on the post-intervention questionnaires, these would be controlled for in the data analysis, as they might influence movement patterns.[24-26]

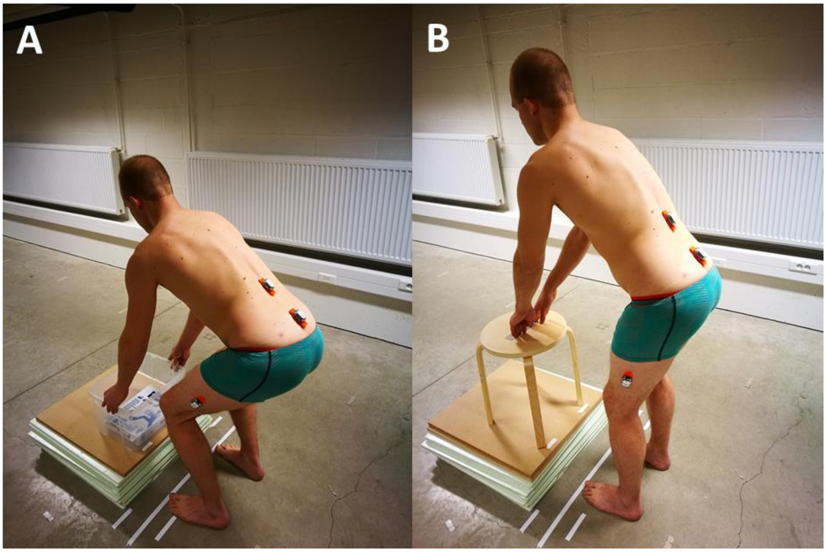

Fig. 1 Movement control tasks. A. Lifting task. B. Waiter's bow.

2.3.3 Equipment

The Valedo®motion research tool (Hocoma, Switzerland) was used to assess the lumbopelvic kinematics and to provide feedback in the sensor groups. This system consists of a laptop and three wireless inertial measurement sensors, which contain a magnetometer, 3D-accelerometer and a 3D-gyroscope. The sensors were placed on the spinous process of L1 and S1, and 20 cm above the lateral femoral condyle (Fig. 1). All three sensors were used for the kinematic assessment, while only the L1 and S1 sensors were used to provide feedback in the sensor groups. Details on the kinematic data acquisition have been previously described.[27]

2.4 Intervention

During the intervention, participants practised the waiter’s bow during three sets of six repetitions while they received their assigned form of feedback. Each set of exercises was separated by one minute of rest. The lifting task was not practised. The feedback in the different groups was provided as follows:

2.4.1 Sensor group

The sensor-feedback was given via an avatar on a computer screen in front of the participants. The avatar was controlled by two movement sensors that were placed on the spinous process of L1 and S1. The upper body of the avatar corresponded with the S1-sensor and the green rectangle with the L1-sensor (Fig. 2). First, the system was calibrated when the participants assumed the starting position so that the green rectangle was placed in the middle of the avatar’s upper body. Participants were instructed to keep the green rectangle on the avatar during the exercises, as this meant that the lumbar curvature was maintained (Fig. 2A). If the rectangle moved anteriorly of the avatar, this corresponded with a lumbar flexion (Fig. 2B), while a posterior displacement indicated a lumbar extension.

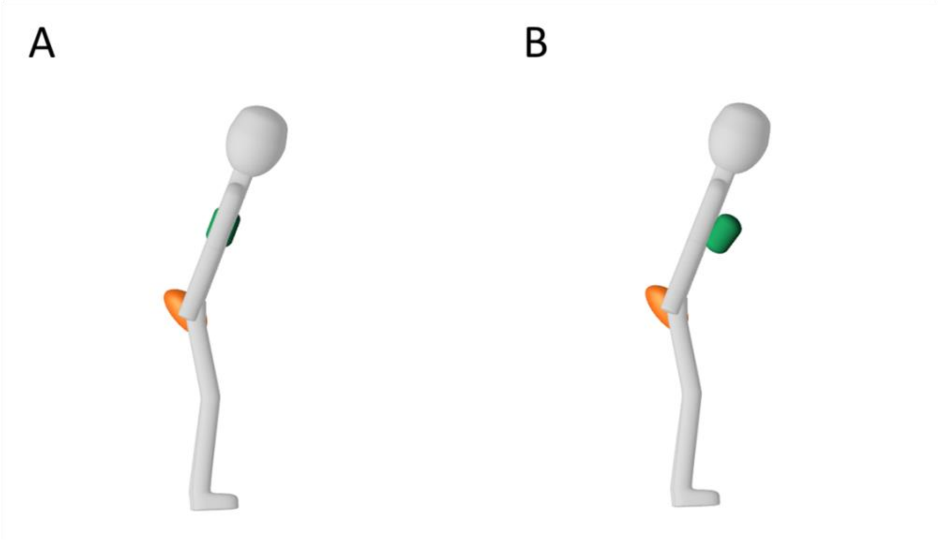

Fig. 2 Sensor-feedback with an avatar. A. The green rectangle is kept on the upper body of the avatar, indicating that the lumbar curvature is maintained. B. The green rectangle moves anteriorly to the avatar’s upper body, indicating a lumbar flexion.

2.4.2 Mirror group

A large mirror was placed laterally to the participants so they could see the stool and their whole body, and observe their spinal curvature during the exercises.

2.4.3 Control group

No feedback was provided.

Before the exercise trials, participants were explained how to use pelvic tilts to adjust the lumbar curvature. Hereafter, they were allowed to perform up to five pelvic tilts, during which participants in the sensor group could see how pelvic movements affected the position of the green rectangle relative to the avatar, participants in the mirror group could observe in the mirror how the pelvic tilts changed their lumbar curvature, while the control group received no feedback.

2.5 Outcome measures for addressing the primary and secondary aims of the study

2.5.1 Primary aim - Effectiveness of feedback

The influence of the different types of feedback on movement control performance and motor learning was of primary interest. Performance can be measured during or shortly after training, whereas motor learning can be assessed with a transfer test.[28] As the participants only practised the waiter's bow, we used the differences between baseline and post-intervention kinematics of the waiter's bow as a measure of performance, while differences in the lifting task kinematics were used as a measure for motor learning. For each repetition, the maximal range of motion in the lumbar spine and hip joint was calculated and expressed in absolute values. Lumbar spine angles were calculated from the L1 and S1 sensors, while hip joint angles were calculated from the S1 and femoral sensors. This method is highly reliable for both tasks in this study (ICCs= 0.89-0.93).[27] The minimal detectable change between two measurements for the lifting task is 5.3° for the lumbar spine and 8.8° for the hip, while for the waiter's bow this is 6.5° and 11.8°, respectively.[27] An improvement in movement control was defined as a decrease in the lumbar range of motion and an increase in the hip range of motion between baseline and post-intervention assessment. In addition to statistical significance, the abovementioned minimal detectable changes were used to interpret the results.

2.5.2 Secondary aim – Comparison between healthy persons and patients with CLBP

The differences between healthy subjects and patients with CLBP in movement control performance improvement and motor learning was evaluated. This was done by comparing the change in lumbopelvic kinematics between baseline and post-intervention between both participant groups. In addition, the evolution of the performance on the waiter's bow task during the intervention was compared. In this way, it could be determined whether healthy participants and patients with CLBP needed the same number of repetitions to achieve an improvement on the waiter's bow.

To investigate whether participants became dependent on the external feedback, the performance on the last exercise trial (with feedback) was compared with the post-intervention performance (without feedback) on the waiter's bow. A significant decline on the post-intervention performance would indicate such dependence.[7]

2.6 Data analysis

The statistical analysis was performed with SAS JMP Pro (Version 12.2). To examine the effectiveness of the feedback and the difference in movement control improvement between healthy participants and patients with CLBP, a multiple linear regression was performed. The following variables were entered in the initial model to predict the differences between baseline and post-intervention kinematics: type of feedback (i.e. control, mirror or sensor), health status (i.e. healthy or CLBP), joint (i.e. lumbar spine or hip) and all their pairwise interactions. To control for the baseline values of the lumbar spine and hip angles, this variable was also put in the initial model. The final model was obtained by stepwise backward regression. The variable with the least significant p-value was left out first, and this was repeated until all the variables reached significance ($p < 0.05$). A Tukey all pairwise comparison was used as a post-hoc test.

A mixed model was used to assess the difference between healthy participants and patients with CLBP in the evolution of the performance on the waiter's bow task. This model was also used to examine the difference between the last repetition of the intervention and the post-intervention performance on the waiter's bow. The same variables from the linear regression were included in the mixed model, but 'repetition number' (i.e. baseline, repetitions during the intervention and post-intervention measurements were numbered) and its pairwise interactions with other variables were added as fixed factors. 'Participant' was used as a random factor to account for multiple measurements for the same participant.

Sample size calculation was based on an effect size (f^2) of 0.2, power of 0.80 and α-level of 0.05. With these parameters, a total sample size of 80 participants was needed. Taking into account an attrition rate of 30% because of baseline performance on the movement control tests, 54 healthy persons and 54 patients with CLBP had to be recruited.

3 Results

The flow of participants through the study is shown in Figure 3. Ten (19%) patients with CLBP and seven (13%) healthy participants were excluded based on their baseline performance on the movement control tasks. No significant differences in demographics (Table 1) and baseline scores on kinematic outcome measures (Table 2, first column) were observed between groups.

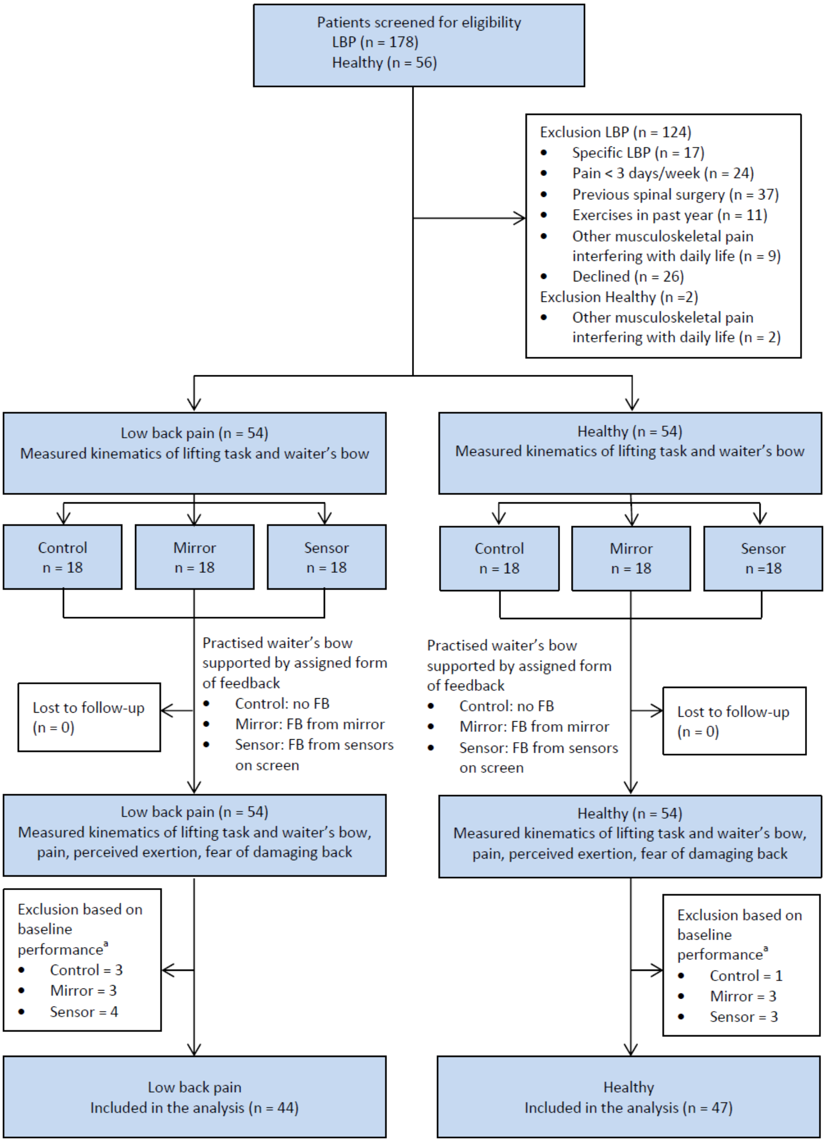

Fig. 3 Design and flow of participants through the trial.

FB= feedback.

[a] Participants were excluded after the trial, based on their performance on the baseline movement control tasks (exclusion criterion set a priori). Because the performance on the baseline kinematic measurements was calculated after trial completion, all participants were measured post-intervention, but only 44 participants in the low back pain group and 47 participants in the healthy group were included in the final analysis.

Table 1 Baseline characteristics of the participants.

Characteristic	Patients with chronic low back pain			Healthy persons			p-value
	Control (n=15)	Mirror (n=15)	Sensor (n=14)	Control (n=17)	Mirror (n=15)	Sensor (n=15)	
Sociodemographic data							
Age (years)	43 (12)	36 (13)	40 (17)	37 (10)	40 (14)	33 (14)	0.31
Gender, n female (%)	5 (33)	7 (47)	6 (43)	10 (59)	6 (40)	8 (53)	0.31
Height (cm)	176 (11)	175 (7)	171 (8)	174 (5)	170 (9)	172 (9)	0.38
Weight (kg)	78 (14)	69 (12)	70 (11)	70 (11)	63 (11)	71 (13)	0.05
LBP Questionnaires							
Onset LBP *(years)*[a]	3 (7)	4 (6)	6 (10)				0.56
NPRS 7 days *(0 – 10)*	4.9 (1.5)	4.5 (1.9)	4.5 (1.4)				0.72
NPRS current *(0 - 10)*	3.1 (2.0)	2.9 (1.9)	3.2 (2.2)				0.93
RMDQ *(0 – 24)*	7.7 (3.5)	7.5 (4.9)	6.6 (3.3)				0.69
TSK *(17 – 68)*	37.9 (5.5)	37.1 (6.9)	37.1 (8.6)				0.94

Data are mean (SD), unless mentioned otherwise. LBP= low back pain, NPRS= Numeric pain rating scale, NPRS 7 days= average pain during the past 7 days measured with a NPRS, NPRS current= current pain measured with a NPRS, RMDQ= Roland-Morris Disability Questionnaire, TSK= Tampa scale for kinesiophobia.

Table 2 Baseline and post-intervention maximal range of motion in the lumbar spine and hip joint.

		Baseline	Post-intervention	Mean difference (95%CI)
Chronic low back pain				
Waiter's bow				
Lumbar spine	Control	17.9 (5.9)	17.5 (6.6)	-0.4 (-2.9 to 2.0)
	Mirror	18.5 (4.3)	15.8 (2.7)	-2.7 (-0.5 to -0.2)
	Sensor	16.2 (6.2)	6.5 (4.7)	-9.7 (-13.9 to -5.5)[a]
Hip	Control	27.8 (16.3)	28.3 (15.8)	0.5 (-4.7 to 5.8)
	Mirror	36.0 (13.7)	38.5 (14.2)	2.5 (-3.4 to 8.4)
	Sensor	31.4 (9.8)	46.1 (11.8)	14.7 (6.4 to 23.0)[a]
Lifting task				
Lumbar spine	Control	23.7 (7.2)	22.0 (10.6)	-1.7 (-5.1 to 1.8)
	Mirror	20.5 (7.2)	18.9 (4.7)	-1.6 (-4.1 to 1.0)
	Sensor	21.0 (7.5)	13.9 (7.8)	-7.2 (-3.7 to -10.7)[a]
Hip	Control	89.2 (13.6)	87.3 (14.7)	-1.9 (-7.9 to 4.1)
	Mirror	91.1 (13.6)	86.3 (19.2)	-4.9 (-11.5 to 1.8)
	Sensor	89.7 (12.8)	95.4 (9.8)	5.7 (-0.1 to 11.5)
Healthy subjects				
Waiter's bow				
Lumbar spine	Control	20.5 (7.3)	18.7 (9.7)	-1.8 (-6.3 to 2.8)
	Mirror	22.2 (7.7)	20.6 (9.8)	-1.6 (-5.1 to 1.8)
	Sensor	21.5 (6.1)	8.2 (4.4)	-13.3 (-17.9 to -9.4)[a]
Hip	Control	26.1 (10.5)	33.4 (13.8)	7.2 (-1.6 to 12.9)
	Mirror	27.7 (12.7)	33.5 (15.1)	5.8 (1.1 to 10.4)
	Sensor	30.7 (10.1)	45.1 (7.4)	14.5 (9.2 to 19.7)[a]
Lifting task				
Lumbar spine				
	Control	24.1 (10.7)	22.4 (11.0)	-1.8 (-3.0 to -0.7)
	Mirror	27.8 (7.0)	26.9 (7.3)	-0.9 (-3.7 to 1.8)
	Sensor	27.0 (8.3)	19.8 (7.0)	-7.1 (-2.6 to -11.7)[a]
Hip	Control	88.0 (13.1)	86.7 (12.7)	-1.3 (-8.8 to 2.1)
	Mirror	92.4 (13.3)	92.6 (7.8)	0.2 (-4.2 to 4.6)
	Sensor	83.9 (14.1)	92.1 (10.7)	8.2 (3.1 to 13.3)

All data are expressed as angles in degrees (°). Data for baseline and post-intervention are mean (SD). Mean difference= post-intervention minus baseline.

[a] Mean difference > measurement error.

3.1 Effectiveness of feedback

The results of the linear regression and post-hoc tests are presented in Table 3 (see Additional table 1 for a detailed sum of squares table). In both the healthy participants and patients with CLBP, the sensor group improved significantly more than the mirror and control group (post-hoc tests, $p < 0.0001$), while no differences were observed between the mirror and control group (post-hoc tests, $p > 0.91$). These results were obtained for both the waiter's bow and the lifting task, as well as for the lumbar spine and hip. The improvements in the sensor groups were also larger than the measurement error (i.e. minimal detectable change), except for the hip during the lifting task (Table 2). There were no between groups differences in the post-intervention questionnaires (see Additional table 2).

Based on the type III sum of squares tables (see Additional table 1), it is clear that the type of feedback is the most important factor contributing to the variance that is explained by the final regression models of the waiter's bow and lifting task, while the factor joint only explains a small proportion. A significant part of the variance that is explained by the final model of the lifting task can be attributed to the baseline scores on the kinematic assessments. Participants who had a worse performance on the baseline lifting task had a larger improvement.

Table 3 Results of the linear regression analysis and post-hoc tests for type of feedback.

Linear regression		Post-hoc multiple comparisons for type of FB		
Fixed effects	p-value	Comparison	Estimated differences between groups (95% CI)	p-value
Waiter's bow				
Initial model				
Health status	0.09			
Type of FB	<0.0001			
Joint	0.01			
Baseline score kinematics	0.06			
Health status*type of FB	0.61			
Health status*Joint	0.71			
Type of FB*Joint	0.94			
Final model				
Type of FB	<0.0001	Mirror minus Control	0.6 (-3.1 to 4.4)	0.91
Joint	0.04	Sensor minus Control	10.6 (6.8 to 14.3)	<0.0001[a]
		Sensor minus Mirror	9.9 (6.1 to 13.7)	<0.0001[a]
Lifting task				
Initial model				
Health status	0.20			
Type of FB	<0.0001			
Joint	0.029			
Baseline score kinematics	0.003			
Health status*type of FB	0.65			
Health status*Joint	0.44			
Type of FB*Joint	0.57			
Final model				
Type of FB	<0.0001	Mirror minus Control	-0.3 (-3.7 to 3.0)	0.97
Joint	0.02	Sensor minus Control	6.9 (3.5 to 10.2)	<0.0001[a]
Baseline score kinematics	0.002	Sensor minus Mirror	7.2 (3.8 to 10.6)	<0.0001[a]

FB= Feedback, Health status= healthy of CLBP, Joint= lumbar spine or hip, Type of FB= sensor, mirror or control.

[a] in favour of the sensor group.

3.2 Comparison between healthy persons and patients with CLBP

The variable health status (i.e. healthy or CLBP) and its interaction with repetition number were not retained in the final mixed model (Table 4). This indicates that patients with CLBP were equally capable of improving lumbopelvic movement control, and that the evolution of the performance on the waiter's bow task was similar between both participant groups (see Fig. 4). These results are further supported by the fact that only a small proportion of the variance that is explained by the final model can be attributed to each of the variables pertaining to our second research question (see Additional table 3 for a detailed sum of squares table). Post-hoc tests also showed that there were no differences between the performance on the last exercise trial and the post-intervention assessment of the waiter's bow. This demonstrates that participants in the mirror and sensor groups did not become dependent on the feedback.

Table 4 Results for the mixed model.

Fixed effects	p-value
Initial model	
Health status	0.40
Type of FB	<0.0001
Joint	<0.0001
Baseline score kinematics	<0.0001
Repetition number	<0.0001
Health status*type of FB	0.83
Health status*Joint	0.01
Type of FB*Joint	0.08
Repetition number*type of FB	<0.0001
Repetition number*Health status	0.28
Repetition number*Joint	0.09
Final model	
Health status	0.38
Type of FB	<0.0001
Baseline score kinematics	<0.0001
Joint	<0.0001
Repetition number	<0.0001
Health status*Joint	0.01
Repetition number*Type of FB	<0.0001

FB= Feedback, Health status= healthy of CLBP, Joint= lumbar spine or hip, Type of FB= sensor, mirror or control.

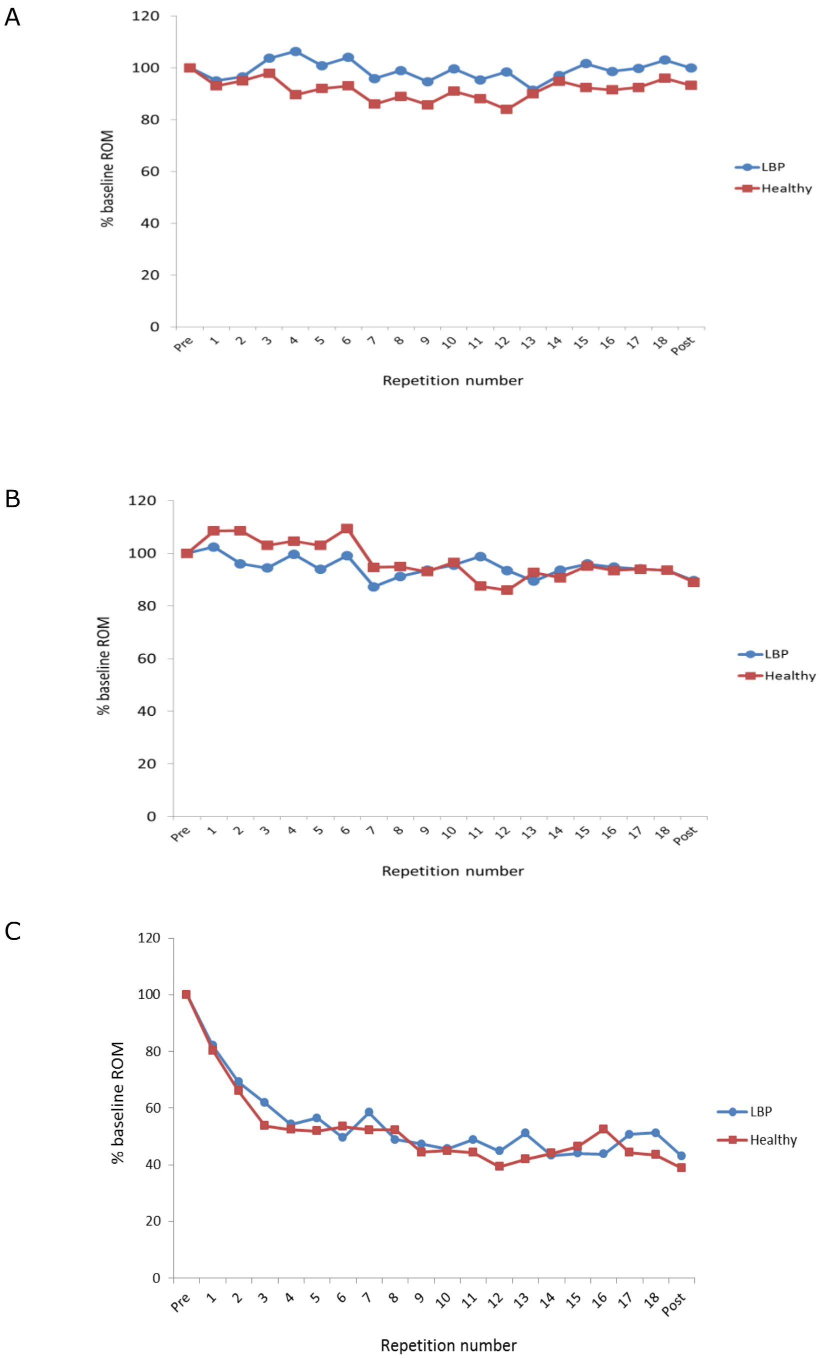

Fig. 4 Evolution of the performance on the waiter's bow in the Control (4A), Mirror (4B) and Sensor (4C) groups throughout the intervention (group means are shown). On the Y-axis, the range of motion (ROM) in the lumbar spine is shown in proportion to the baseline ROM. A decrease in ROM indicates an improvement in movement control.

4 Discussion

The primary aim of this study was to compare the effectiveness of different types of external feedback to improve lumbopelvic movement control in healthy persons and patients with CLBP. Our results show that sensor-based postural feedback was more effective to improve lumbopelvic movement control than feedback from a mirror or no feedback. Furthermore, being provided with feedback from a mirror did not lead to better results than receiving no feedback at all.

We hypothesise that the lack of improvement in the mirror group could be explained by the difficulty for unexperienced persons to visually detect changes in the lumbar curvature during the waiter's bow. Although physiotherapists can reliably assess the waiter's bow by observation, observer training may play an important role in this assessment.[29] Possibly, a longer teaching and familiarisation period before the intervention could have enhanced the effectiveness of the mirror-feedback. In contrast, the very short introduction to the sensor-feedback was sufficient to improve lumbopelvic movement control. We believe that the avatar provided more accurate and easy-to-understand feedback, which required no advanced training in order to interpret it correctly. It has been shown that abstract visualisations can be more effective than very realistic feedback (e.g. via a video or mirror) because they can provide information about key features of the task only, without overwhelming the participants with irrelevant information.[8] Participants in the sensor group only had to look at the green dot relative to the avatar's upper body, while participants in the mirror group could also see movements in other body regions that were irrelevant to the task. In addition, the screen displaying the avatar could be placed in front of the participants, whereas the mirror had to be positioned laterally to visualise the movements in the sagittal plane. Although this difference in position could be interpreted as a confounding factor because participants in the mirror group had to turn their heads in order to view their spinal curvature, the possibility to place the computer screen in the most convenient position should rather be considered as an inherent advantage of the sensor-feedback. Finally, the improvements on the lifting task were partially explained by the baseline kinematic scores. Participants who performed worse on the lifting task at baseline assessment had a significantly larger improvement, which indicates that the motor learning effect was more pronounced in these participants. This might be explained by the fact that persons who performed worse at the baseline lifting task also had a larger potential for improvement.

Besides a mirror, various other types of conventional feedback, including tape or palpation,[10] can be used to support patients during lumbopelvic movement control exercises. The rationale for comparing the sensor-based feedback to feedback from a mirror was twofold: First, a mirror is frequently being used or recommended to provide postural feedback during lumbopelvic movement control exercises.[10,30-32] Second, and more importantly, both the mirror and sensors provided visual feedback, whereas palpation and a tape provide tactile feedback. Because visual motion detection is processed differently than tactile motion detection,[33] we chose to compare the sensor feedback to feedback from a mirror.

Healthy subjects and patients with CLBP were equally capable of improving lumbopelvic movement control. It has been suggested that pain could negatively influence skill acquisition and motor learning by distracting people from the task they are performing.[15] However, this distraction mainly occurs when the pain is more intense, unfamiliar or unexpected.[17] The patients with CLBP in our study did not report an increase in pain during the exercise trials and there is no reason to assume that the pain they felt was unexpected or unfamiliar. Therefore, it is unlikely that patients with CLBP were distracted from the movement task. Pain can also affect proprioceptive acuity and impair the intrinsic feedback system.[34] When less reliable intrinsic feedback is available, the dependency on the extrinsic feedback may increase.[7] Overall, patients with CLBP have decreased lumbosacral proprioception compared to healthy persons,[16,35] so it can be argued that removing the external feedback could influence the performance on the waiter’s bow more in patients with CLBP than in healthy participants. On the other hand, these proprioceptive impairments may be position specific (e.g. sit versus stance)[35] and little is known about proprioception during dynamic tasks,[16] such as the ones in the present study. Our results show that omitting the external feedback had no influence on the performance on the waiter's bow in both participant groups. This suggests that patients with CLBP also used information from the sensorimotor system to adjust their spinal curvature during the exercise trials,[8] and that they did not rely more on the external feedback than healthy subjects. The improvements on the lifting task in the sensor groups further support this notion, as it indicates that both participant groups were able to transfer their newly learned skills to a different task. Therefore, it seems appropriate to use concurrent sensor-based feedback during the initial learning phase of movement control tasks in patients with CLBP.

Several limitations apply to this study. First, motor learning was only assessed with a transfer test, and not with a retention test. Both the transferability of practised skills and the long-term retention effects are important aspects of motor learning.[28] Because it is impossible to provide movement control training during every single activity an individual needs to perform, persons should be able to implement their newly acquired skills during activities that were not practised. In addition, the movement control improvements should be retained in the long term. However, because a retention test was not included in this study, we cannot make any statements regarding the longstanding effects of the sensor-based feedback. Second, the measurements were performed in a laboratory setting. It would be valuable to assess the transfer of learned movement skills to real life settings. However, from a technical point of view, this would be very challenging. Third, the mobility of the lower limb joints was not evaluated at baseline assessment. According to the concept of relative flexibility, a restriction in one joint could influence the movements in an adjacent joint.[6] Especially during the lifting task, more end range movements were necessary in the hip joint. As such, a restriction in hip joint mobility could have influenced the lumbar movements. On the other hand, participants with any physical problems other than LBP (e.g. hip or knee pain) that interfered with daily life activities were excluded from this study. Therefore, we believe it is unlikely that a (pathological) restriction of lower limb joint mobility would have significantly influenced the movement patterns in the lumbar spine. Finally, our measurement and feedback system only contained three sensors. Due to these technical limitations, we could only measure the movements in the lumbar spine and hip joint. Consequently, we cannot exclude that some patients might have used compensatory movements in the thoracic spine while performing the movement control tasks. On the other hand, the reduction in lumbar ROM in the sensor group was accompanied by an increase in hip joint motion, indicating movements in the hip joint and lumbar spine were coupled.

5 Conclusions

The recent development of rehabilitation technologies creates new possibilities for therapists and patients to support the rehabilitation process. As such, evaluating the effectiveness of these rapidly evolving technological systems poses an important challenge. The present study shows that sensor-based postural feedback is more effective than feedback from a mirror or no feedback to improve lumbopelvic movement control in the short term. Patients with CLBP were equally capable of improving lumbopelvic movement control as compared to healthy participants. However, our results should be interpreted in light of several limitations such as a lack of retention test and the fact that the intervention was restricted to a single intervention session. Future research should address these limitations and evaluate whether supporting exercises with sensor-based feedback leads to larger improvements in pain and disability compared to conventional exercise therapy.

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Additional table 1 Type III sum of squares table of the final models of the regression analyses

	Nparm	DF	Sum Sq	Mean Sq	F Ratio	p-value
Waiter's bow						
Type of FB	2	2	4159.99	2079.99	26.90	<0.0001
Joint	1	1	303.54	303.54	3.93	0.049
Lifting task						
Type of FB	2	2	1953.44	976.72	15.97	<0.001
Joint	1	1	319.79	319.79	5.23	0.02
Baseline score kinematics	1	1	592.64	592.64	9.69	0.002

FB= Feedback

Additional table 2 Results for post-intervention questionnaires

	Patients with CLBP			Healthy persons			p-value
	Control	Mirror	Sensor	Control	Mirror	Sensor	
Pain (*0 to 10*)	3 (2 to 4)	2 (0 to 3)	3 (0 to 5)	0 (0 to 0.5)	0 (0 to 0)	0 (0 to 1)	
Pain difference *(-10 to 10)*	0 (-2 to 0)	1 (-1 to 2)	0 (-0.5 to 1)	0 (-0.5 to 0)	0 (0 to 0)	0 (-1 to 0)	0.32
Fear of damage *(0 to 10)*	0 (0 to 1)	0 (0 to 1)	0 (0 to 1)	0 (0 to 0)	0 (0 to 0)	0 (0 to 0)	0.18
Borg scale *(6 to 20)*	9 (7 to 11)	8 (7 to 12)	9 (7 to 10)	7 (6 to 8)	6 (6 to 8)	9 (6 to 11)	0.10

Data are median (IQR). Fear= fear of damaging the lumbar spine, Pain= average pain intensity during the intervention, Pain difference= pain baseline minus average pain during the intervention (a negative value indicates an increase in pain).

Additional table 3 Type III sum of squares table for the mixed model analysis

	NumDF	DenDF	Sum Sq	Mean Sq	F-value	p-value
Health status	1	87.0	32.9	32.9	0.79	0.38
Type of FB	2	87.0	1213.4	606.7	14.57	<0.0001
Baseline score kinematics	1	3551.5	8813.3	8813.3	211.69	<0.0001
Joint	1	3510.6	15455.1	15455.1	371.24	<0.0001
Repetition number	19	3488.0	6707.0	353.0	8.47	<0.0001
Health status*joint	1	3492.5	247.5	247.5	5.94	0.01
Repetition number*Type of FB	38	3488.0	5545.8	145.9	3.51	<0.0001

FB= feedback

Chapter III

Study 5

Virtual reality distraction induces analgesia in patients with chronic low back pain: a randomised controlled trial.

Pain, *under review*.

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Abstract

Attentional distraction from pain has been shown to be largely ineffective for obtaining an analgesic effect in patients with chronic pain when compared to a control condition. It has been hypothesised that this may be due to the non-engaging types of distraction that have been used so far. Moreover, it is suggested that the analgesic effects of distraction may be attenuated by pain-related cognitions and emotions, as they may increase the attention to pain. In this randomised controlled trial, patients with chronic low back pain in the intervention group (n= 42) performed a single exercise session with interactive VR games, while those in the control group (n= 42) performed the same exercises without VR games. We investigated whether VR distraction had an analgesic effect during and immediately after the exercises, and whether it reduced the time spent thinking of pain during the exercises. We further assessed whether baseline measures of pain intensity, pain-related fear and pain catastrophising moderated the effects of VR distraction. Our results showed that VR distraction had an analgesic effect during and immediately after the exercises, and it also reduced the time spent thinking of pain. None of the baseline measures moderated the effects of VR distraction.

1 Introduction

Attentional distraction, defined as shifting the attention away from the pain, is a commonly used strategy in pain management.[1,2] The analgesic effects of distraction have mainly been investigated during experimentally induced pain in healthy persons or during acute procedural pain (e.g. needle pain). Although some of these studies have failed to demonstrate an analgesic effect of distraction,[3,4] the majority of studies have shown that distraction does reduce pain in these populations.[5-9] However, a recent meta-analysis reported that distraction did not have an analgesic effect in patients with chronic pain when compared to a control condition without specific instructions.[2]

Various hypotheses have been postulated to explain the lack of distraction induced analgesia in patients with chronic pain. For example, patients with chronic pain have been shown to selectively pay attention to pain-related information, [10,11] and as a consequence, they might be less easily distracted from it. [2,12] This attentional bias to pain develops when the pain is experienced as threatening, and as such, this bias is often associated with higher levels of pain-related fear and pain catastrophizing.[10,11] However, the moderating effects of pain-related cognitions and emotions on the effectiveness of distraction in patients with chronic pain are equivocal.[13-17] Further, it is hypothesized that the type of distraction may play a role. Evidence is emerging that the attention to pain should be considered from a motivational perspective.[5,18] It is thought that in order to draw the attention away from the pain, the competing stimulus should be sufficiently engaging.[19] In this respect, interactive virtual reality (VR) games may prove to be a promising too,l [20-24]as they are typically considered to be motivating.[25] In some randomized controlled trials, VR games have already been integrated into rehabilitation programs for patients with chronic pain.[26-28] However, none of these studies have specifically investigated whether patients experienced less pain while being immersed in a VR environment. As such, the available evidence showing that VR distraction may have an analgesic effect in patients with chronic pain almost exclusively comes from uncontrolled studies with small sample sizes,[29-38] so firm conclusions cannot be drawn. In addition, the potential influence of pain-related cognitions and emotions on the analgesic effects that VR distraction may have on chronic pain has not been investigated.[39] Therefore, more research is needed to address these shortcomings.

In this study, patients with chronic low back pain (CLBP) performed clinically relevant exercises during a single intervention session. *First*, we investigated whether performing these exercises in a VR environment had an influence on the pain intensity and the time spent thinking of pain during the exercises, when compared to a control group who performed the same exercises without VR distraction. *Second*, the pain intensity immediately after the exercises was assessed because distracting patients with CLBP during an active task may paradoxically increase the pain intensity after this task.[15] *Finally*, we investigated the influence of baseline measures of pain intensity, pain-related fear and pain catastrophising on the effectiveness of the VR distraction.

2 Methods

2.1 Participants

Eighty-four patients following treatment for CLBP were included. Inclusion criteria were an age of 18 to 65 years old, sufficient knowledge of the Dutch language, diagnosis of chronic nonspecific low back pain (>3 months, ≥3 days/week) by a physician, a baseline pain score between 3 and 8 on a 0 to 10 numeric pain rating scale and the ability to perform pelvic tilt exercises in a standing position. Participants were excluded if they had previous spinal surgery, recent (< 6 months) spinal infiltrations, signs or symptoms of nerve root involvement, an underlying serious pathology (e.g. multiple sclerosis), fibromyalgia, confirmed or suspected pregnancy and experience with VR rehabilitation. All participants gave written informed consent before being included in the study. Ethical approval was obtained from the Ethics Committees of Hasselt University and Jessa Hospital, Belgium (approval number 15.128/REVA15.11).

2.2 Recruitment and randomisation

Recruitment was performed at the Jessa Hospital (Belgium) and took place between February 2016 and November 2018. At the moment of recruitment, all subjects were participating in an outpatient rehabilitation program for CLBP. After baseline assessment, participants were randomised in a VR-group or a control group by using sequentially numbered, sealed opaque envelopes that were prepared by a person not further involved in the study.

2.3 Intervention

We used a single-session intervention, which consisted of 2 x 2 minutes of pelvic tilt exercises in the sagittal plane, with 30 seconds of rest in between. Pelvic tilt exercises are often used in the rehabilitation of patients with CLBP, and their purpose is to (re)gain movement control of the lumbar spine and pelvis.[40,41] The latter can be important, as it has been suggested that poor movement control may be an underlying mechanism contributing to the persistence of CLBP.[42] In the current study, the pelvic tilt exercises were performed in a standing position with slightly bent knees and participants placed their hands on the side of their pelvis to guide the pelvic movements.

Upon arrival, participants were explained that they first had to complete various questionnaires, after which they would be asked to perform pelvic tilt exercises for a few minutes. Participants were told that after the exercises, they would have to answer a few short questions concerning their experiences with the exercises. No reference was made to our interest in pain intensity or the potential effect of VR distraction. Just before the start of the intervention, participants received instructions on how to perform the pelvic tilts. The experiments took place in a separate room in the hospital, with no other patients present. During the experiments, an investigator was present in the room and sat a few meters behind the participant, outside the participant’s field of vision. During the intervention, the investigator visually checked whether the exercises were performed correctly, but no feedback was provided. If participants failed to perform the exercises in a correct way (e.g. by making whole-body movements instead of pelvic tilts), they would be excluded from further analyses.

2.3.1 Virtual Reality group

The VR-group played 2 different games (2 minutes each), which had to be controlled by pelvic tilts in the sagittal plane. To play the games, a wireless motion sensor (Valedo®Pro, Hocoma, Switzerland) was placed on the sacrum at the S2-level using double sided tape (an additional sensor at the L1-level was used for calibration of the system). The sensor measures with an accuracy of 0.1° and a frequency of 50Hz. The sensor-signals were sent to a laptop that was connected to a high definition TV screen (47 inch) on which the games were displayed. During the games, participants stood in front of TV-screen at a distance of 2.5 meters and the sound of the TV was turned on (Fig. 1A). The goal of the first game was to collect points by guiding a caterpillar through hoops and by catching objects that were floating in the air (Fig. 1B). During the second game, points could be gained by guiding a fish through a cave and to collect shells, while avoiding hitting the cave walls or bumping into other fish (Fig 1C). The caterpillar and fish could be steered upwards or downwards by tilting the pelvis in an anterior or posterior direction. Before the start of the intervention, the purpose of the games was explained and participants were instructed how to play them (i.e. with pelvic tilts). No feedback was given during the games.

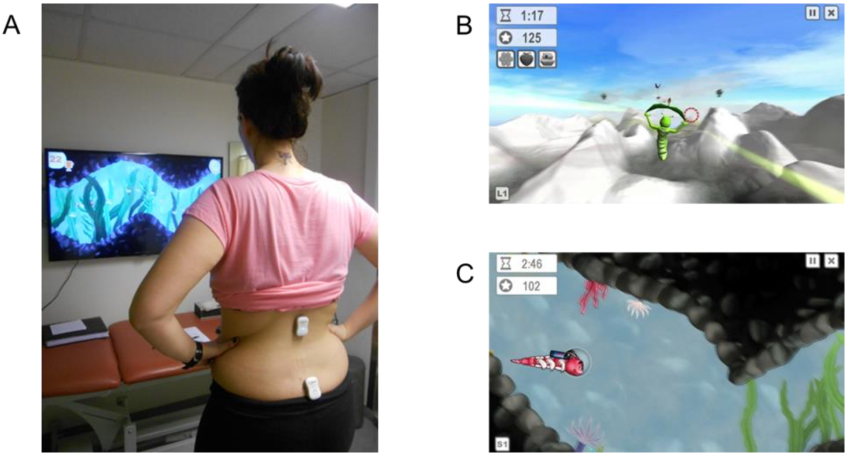

Fig 1. A: Participant playing the VR games. B-C: VR games

2.3.2 Control group

The control intervention was conducted in the same room as the VR intervention. During the control intervention, participants stood in exactly the same spot as those in the VR group, but with the TV screen switched off. The control group performed pelvic tilts in the sagittal plane according to a beep tone. The control group performed the pelvic tilts in the sagittal plane according to a beep tone. The first time participants heard the tone, they had to tilt their pelvis anteriorly and keep it in an anteriorly tilted position until the next beep, after which participants tilted the pelvis posteriorly, and so on. Participants had to tilt their pelvis 46 times during the first two minutes, and 54 times during the second two minutes. The tempo of the beep tones was varied, so that participants sometimes had to tilt their pelvis faster or slower. The number and the tempo of the beep tones were based on a pilot trial that was conducted prior to the current study. During this pilot trial, 12 persons fulfilling the criteria of the current study performed the VR-games as described above, while the movements of the pelvis were recorded with a digital video camera. Two research assistants, not further involved in the study, counted the number of pelvic tilts and assessed the tempo of the pelvic movements independently from each other. Based on these observations, audio files for each of the two games were created prior to the main study in order to mimic the number and tempo of pelvic tilts during the VR games as closely as possible. The participants of the pilot trial were not included in this study.

2.4 Assessments and outcome measures

2.4.1 Baseline assessments

Sociodemographic data: Participants were asked to provide information on their age, weight, height, sex and duration of LBP.

Numeric Pain Rating Scale (NPRS)[43]: Participants were asked to indicate the average intensity of their LBP over the past 7 days and the intensity of their current LBP on a 0 to 10 numeric rating scale (0= no pain, 10= worst imaginable pain). The 11-point NPRS has been widely used to measure pain intensity in a CLBP population and has been recommended to be used in clinical trials.[44,45]

Roland Morris Disability Questionnaire (RMDQ)[46]: The RMDQ contains 24 questions about the effect of LBP on daily activities, which have to be answered with yes or no. A higher score (range 0-24) represents a higher level of disability. The RMDQ has been shown to be valid and reliable in a CLBP population.[43]

Pain Catastrophising Scale (PCS)[47]: The PCS contains 13 statements relating to the patients' negative thoughts and feelings during pain. Each statement has to be answered on a 5-point scale (0= not at all, 4= always), resulting in a score between 0 and 52. A higher score corresponds with a higher level of pain catastrophising. The PCS is valid and reliable in a CLBP population.[48] Cronbach's alpha of the PCS in this study was 0.91.

Tampa Scale for Kinesiophobia (TSK)[49]: The TSK is a questionnaire containing 17 items to assess subjective ratings of fear of movement/re-injury due to physical activity. The total score ranges between 17 and 68, with a higher score indicating a higher level of kinesiophobia. The TSK is valid and reliable in patients with CLBP.[43] Cronbach's alpha of the TSK in this study was 0.75

2.4.2 Post-intervention assessments

Immediately after the exercises, participants completed the following three questions on a 0 to 10 numeric rating scale. Question one: 'What was the average intensity of your low back pain during the exercises?' (0= no pain, 10= worst imaginable pain). Question two: 'How much did you think of your low back pain during the exercises?' (0= not at all, 10= all the time).[50] Question three: 'What is the intensity of your low back pain at this moment?' (0= no pain, 10= worst imaginable pain). These assessments were performed after the intervention in order not to create conflicting attentional processes, i.e. asking participants to report pain during the exercises while the purpose of the VR intervention was to distract them from the pain.[2]

After the abovementioned questions, two additional questions were asked. Based on previous research,[25] the VR games used in this study were expected to be motivating. To confirm this, participants in the VR group were asked to answer the following question, which was derived from the Immersive Experience Questionnaire[51]: 'To what extent did you feel motivated while playing the virtual reality games?' (1= not at all, 7= a lot). Second, we assumed that participants would not perceive the exercises as harmful. We checked this assumption, because the perceived harmfulness during a movement task has been shown to be related to the pain experience during that task.[52] Therefore, participants in both groups were asked to answer the following question: 'How harmful did you think the exercises were for your lower back?' (0= not harmful at all, 10= extremely harmful).

2.5 Outcome measures

Primary outcome: The difference between baseline pain intensity and the pain intensity experienced during the exercises (= pain difference during) was the primary outcome. This difference was obtained by subtracting the pain intensity during the exercises from the baseline pain intensity. A positive value thus indicates an improvement.

Secondary outcomes: (1) The difference between baseline pain intensity and the pain intensity experienced immediately after the intervention (= pain difference after), (2) the time spent thinking of pain during the exercises and (3) the number of pelvic tilts performed by the participants were the secondary outcomes. The pain difference after the exercises was obtained by subtracting the pain intensity after the exercises from the baseline pain intensity. A positive value indicates an improvement. The number of pelvic tilts in both groups was assessed in the same way as during the pilot trial. If between group differences would be present, or the number of pelvic tilts would be correlated with any of the outcomes, this factor would be controlled for in the analyses.

2.6 Sample size calculation

Because this is the first randomised controlled trial investigating the analgesic effects of VR distraction in patients with CLBP, and similar studies in other chronic pain populations are lacking, we based our sample size calculation on effect sizes reported in meta-analyses including studies on experimentally induced and acute procedural pain. Large effect sizes of VR distraction for pain reduction ranging between 0.9[23] and 0.94[53] were reported in these meta-analyses. However, when only the effects on clinical pain were considered, Kenney et al.[23] reported a smaller effect size of 0.62. Given that we assessed clinical pain in the current study, the most conservative estimate of 0.62 for the primary outcome measure (pain improvement during the distraction) was used. Together with an alpha-level of 0.05 and power of 0.8, a total of 84 participants needed to be included in this study.

2.7 Statistical analyses

All statistical analyses were performed with JMP Pro version 14.1 (SAS institute, Cary, NC). To investigate the effects of VR distraction on the pain intensity, a repeated measures ANOVA was performed with group (VR vs control) as between groups factor and time (pain difference during vs pain difference after) as within group factor. The effects of VR distraction on the time spent thinking of the pain were assessed with a t-test for independent samples.

The influence of baseline measures of pain-related fear, pain catastrophising and pain intensity on the effectiveness of VR distraction was assessed using both continuous and dichotomised scores of the baseline measures. Using dichotomised scores lowers the power to detect significant effects, but it facilitates the clinical interpretation of the results.[54] Therefore, we used both approaches to analyse our data. The dichotomisation of the baseline measures into 'low' and 'high' groups was done according to Linton et al.[55] First, we performed a median split of the TSK, PCS and pain intensity scores, after which we compared them to previously reported clinically relevant cut-off values. For both groups in the current study, the median scores for the TSK and PCS were 37 and 22, respectively. The clinically relevant cut-off values reported in the literature for the TSK range between 37 and 40, whereas for the PCS these scores range between 22 and 30.[47,55-58] Given that the median scores of the current study fell within these ranges, albeit on the lower end of the spectrum, we continued using the median splits. The median baseline pain score in the current study was 4.5/10 for both the VR and control group. Pain scores are often separated into three categories, and in patients with LBP, a score on the NPRS between 1-4 has been reported as mild, between 5-6 as moderate and ≥ 7 as severe.[59,60] Using the median score (4.5/10) of the current study, participants in the low baseline pain groups had scores of 3-4/10 which can be considered as mild pain, whereas participants in the high baseline pain groups had scores between 5-8/10, being moderate to severe pain. In the control group, these median splits resulted in mean scores in the respective low and high groups for the TSK of 31.0 (SD= 4.2) and 42.5 (SD= 3.5), for the PCS of 14.9 (SD= 5.6) and 30.3 (SD= 5.3), and for the baseline pain of 3.7 (SD= 0.5) and 6.0 (SD= 0.8). Regarding the VR group, the mean scores in the respective low and high groups for TSK were 32.9 (SD= 3.0) and 42.3 (SD= 3.2), for the PCS they were 14.5 (SD= 5.9) and 31.6 (SD= 7.7), and for baseline pain intensity they were 3.4 (SD= 0.5) and 6.2 (SD= 0.9). To assess the moderating effects of the baseline measures on the VR distraction, for each dependent variable (pain difference during, pain difference after and the time spent thinking of pain) multiple linear regression models were constructed and 2 x 2 ANOVAs were performed, depending whether the baseline scores were continuous or dichotomous. In all of the regression models and ANOVAs, we included group (VR vs Control) and the baseline measure (i.e. pain-related fear, pain catastrophising or pain intensity) as main effects, and a group by baseline measure as interaction effect. Post-hoc tests and pre-planned contrast analyses were conducted when appropriate. Partial eta-squared (η_p^2) and Cohen's *d* effect sizes were calculated.[61] The alpha level for statistical significance was set at $p < 0.05$.

Before running all the analyses, we checked whether the number of pelvic tilts differed between the VR and control group, and whether they were correlated with any of the outcomes in the VR group. Four participants in the control group missed a maximum of 2 pelvic tilts during the intervention, while all of the other participants in the control group performed the set number of pelvic tilts (n= 100). The mean number of pelvic tilts performed in the VR group was 98.1 (SD= 15.6), which was not significantly different from the control group (p= 0.44). In addition, there was no correlation between the number of pelvic tilts and any of the outcome measures in the VR group (all correlation coefficients ≤0.12, all p-values ≥ 0.44). Therefore, the number of pelvic tilts were not included in further analyses.

3 Results

3.1 Participant characteristics

A total of 401 persons were screened for eligibility, of which 84 participants were included. Reasons for exclusion and the flow of participants through the study can be found in Additional Figure 1. None of the participants had to be excluded because of an incorrect performance of the exercises. An overview of the participants' characteristics can be found in Table 1. No significant between groups differences were present for any of the baseline measures.

Table 1 Baseline characteristics participants

	Control group (n=42)		VR-group (n=42)		p-value
	Mean	(SD)	Mean	(SD)	
Sex *(n female, %)*	27	(64%)	27	(64%)	1.00
Age *(years)*	44.2	(11.9)	42.1	(11.5)	0.41
BMI *(kg/m²)*	26.7	(5.0)	26.8	(4.8)	0.92
Duration LBP *(years)*	10.6	(10.2)	10.8	(10.6)	0.84
Pain past 7 days *(0-10)*	5.5	(1.6)	5.3	(1.6)	0.68
Baseline pain *(0-10)*	4.9	(1.4)	4.8	(1.6)	0.83
RMDQ *(0-24)*	10.9	(4.3)	11.4	(3.8)	0.57
TSK *(17-68)*	36.2	(6.9)	37.0	(5.6)	0.59
PCS *(0-52)*	22.2	(9.4)	22.7	(10.9)	0.86

BMI= Body mass index, LBP= low back pain, PCS= Pain Catastrophising Scale, RMDQ= Roland Morris Disability Questionnaire, TSK= Tampa Scale for Kinesiophobia

3.2 Effectiveness of VR distraction

3.2.1 Effects of VR distraction on pain intensity

A repeated measures ANOVA showed a main effect for group ($F_{(1,\ 83.6)}$= 28.39, p< 0.0001, η_p^2= 0.26) and for time ($F_{(1,\ 80.9)}$= 7.42, p= 0.008, η_p^2= 0.08), and a group by time interaction ($F_{(1,\ 80.9)}$= 9.3, p= 0.003, η_p^2= 0.10). Compared to the control group, the VR-group had a significantly larger reduction in pain intensity during the exercises (VR group M= 1.66, SE= 0.25; Control group M= -0.55, SE= 0.26; Difference= 2.20, SE= 0.36, $t_{80.9}$= 6.11, p < 0.0001, *d*= 1.29 (95% CI= 0.82-1.76)) and after the exercises (VR group M= 0.81, SE= 0.25; Control group M= -0.50, SE= 0.26; Difference= 1.31, SE= 0.36, $t_{80.9}$= 3.64, p< 0.003, *d*= 0.85 (95% CI= 0.40-1.29)).

3.2.2 Effects of VR distraction on the time spent thinking of pain

Participants in the VR group spent significantly less time thinking of their pain during the exercises compared to participants in the control group (VR group M= 2.26, SD= 2.55; Co group M= 5.52, SD= 2.41; Difference= 3.26, t_{82}= 6.01, p< 0.0001, *d*= 1.31 (95% CI= 0.84–1.78)).

3.3 Influence of baseline parameters on the effectiveness of VR distraction

For brevity, and because of an easier interpretation from a clinical perspective, only the results for the dichotomised scores are presented in the main text. Of importance, the factors that were statistically significant in the ANOVAs using the dichotomised scores were identical to those in the regression models when using the continuous scores. The results for the regression models can be found in Additional Tables 1 to 3.

3.3.1 Influence on the difference between pain intensity at baseline and during the exercises

Regarding pain-related fear, a main effect for group ($F_{(1, 80)}$= 35.86, p< 0.0001, η_p^2= 0.31) and TSK ($F_{(1, 80)}$= 11.80, p= 0.0009, η_p^2= 0.13) was present. There was no interaction effect ($F_{(1, 80)}$ = 0.37, p= 0.54). Patients in the low TSK groups had larger improvements than those in the high TSK groups (Mean difference= 1.24, SE= 0.36). When assessing the influence of pain catastrophising, there was a main effect for group ($F_{(1, 80)}$= 36.47, p < 0.0001, η_p^2= 0.31) and pain catastrophising ($F_{(1, 80)}$ = 6.65, p= 0.01, η_p^2 = 0.08) but no interaction effect ($F_{(1, 80)}$= 0.01, p= 0.93). The improvements in the low PCS groups were larger than those in the high PCS groups (Mean difference= 0.95, SE= 0.37). For baseline pain intensity, there was only a significant main effect for group ($F_{(1, 80)}$= 34.01, p < 0.0001, η_p^2= 0.29). No main effect for baseline pain intensity ($F_{(1, 80)}$= 1.73, p= 0.19) and no interaction effect ($F_{(1, 80)}$= 0.09, p= 0.75) were present. More detailed results can be found in Table 2.

Table 2 Pain difference during exercises: Planned contrasts for low and high scores on baseline parameters

	Group		Between group differences		
	Control	VR	$F_{(1,\ 80)}$	P-value	ES (η_p^2)
TSK					
Low	-0.08 (0.34)	2.29 (0.33)	24.72	<0.0001	0.24
High	-1.11 (0.38)	0.83 (0.19)	12.90	0.0006	0.14
PCS					
Low	-0.13 (0.35)	2.13 (0.36)	20.21	<0.0001	0.20
High	-1.05 (0.39)	1.15 (0.38)	16.53	0.0001	0.17
NPRS					
Low	-0.86 (0.38)	1.48 (0.38)	18.88	<0.0001	0.19
High	-0.24 (0.38)	1.86 (0.38)	15.23	0.0002	0.16

Group means (SE) of the differences between pain intensity at baseline and during the exercises are presented. A negative value indicates an increase in pain intensity and a positive value indicates a decrease in pain intensity compared to baseline.

3.3.2 Influence on the difference between pain intensity at baseline and after the exercises

For pain-related fear, there was a main effect for group ($F_{(1,\ 80)}= 17.34$, $p< 0.0001$, $\eta_p^2= 0.18$) and for TSK ($F_{(1,\ 80)}= 19.04$, $p < 0.0001$, $\eta_p^2= 0.19$), but no interaction effect ($F_{(1,\ 80)}= 0.13$, $p= 0.72$). The low TSK groups had a larger improvement than the high TSK groups (Mean difference= 1.38, SE= 0.32). Regarding pain catastrophising, a main effect for group ($F_{(1,\ 80)}= 16.45$, $p< 0.0001$, $\eta_p^2= 0.17$) and PCS ($F_{(1,\ 80)}= 5.97$, $p< 0.02$, $\eta_p^2= 0.07$) was present, but there was no interaction between these two factors ($F_{(1,\ 80)}= 0.31$, $p= 0.58$). Participants in the low PCS groups experienced a larger improvement than participants in the high PCS groups (Mean difference= 0.82, SE= 0.34). Again, for baseline pain intensity there was only a main effect for group ($F_{(1,\ 80)}= 14.99$, $p= 0.0002$, $\eta_p^2= 0.16$), but not for baseline pain intensity ($F_{(1,\ 80)} = 3.86$, $p= 0.22$), and no interaction effect was found ($F_{(1,\ 80)}< 0.01$, $p= 1.00$). Details on the influence of the baseline parameters on the pain difference during exercises are presented in Table 3.

Table 3 Pain difference after exercises: Planned contrasts for low and high scores on baseline parameters

	Group		Between group differences		
	Control	VR	$F_{(1, 80)}$	P-value	ES (η_p^2)
TSK					
Low	0.17 (0.29)	1.38 (0.29)	8.22	0.005	0.09
High	-1.32 (0.33)	0.11 (0.34)	9.14	0.003	0.10
PCS					
Low	-0.04 (0.32)	1.14 (0.33)	6.61	0.01	0.08
High	-1.05 (0.35)	0.50 (0.34)	9.92	0.002	0.11
NPRS					
Low	-0.71 (0.35)	0.62 (0.35)	7.45	0.008	0.09
High	-0.29 (0.35)	1.05 (0.35)	7.45	0.008	0.09

Group means (SE) of the differences between pain intensity at baseline and after the exercises are presented. A negative value indicates an increase in pain intensity and a positive value indicates a decrease in pain intensity compared to baseline.

3.3.3 Influence on the time spent thinking of pain

Regarding pain-related fear, a main effect for group ($F_{(1, 80)} = 37.06$, $p < 0.0001$, $\eta_p^2 = 0.32$) and TSK ($F_{(1, 80)} = 5.67$, $p < 0.02$, $\eta_p^2 = 0.07$) was present, but there was no interaction effect ($F_{(1, 80)} = 0.11$, $p = 0.74$). Patients in the low TSK groups spent less time thinking of their pain compared to patients in the high TSK groups (Mean difference= 1.27, SE= 0.53). For pain catastrophising, there was a main effect for group ($F_{(1, 80)} = 42.46$, $p < 0.0001$, $\eta_p^2 = 0.35$) and PCS ($F_{(1, 80)} = 14.09$, $p = 0.0003$, $\eta_p^2 = 0.15$), but no interaction effect was found ($F_{(1, 80)} = 0.002$, $p = 0.97$). The patients in the low PCS groups thought less of their pain than those in the high PCS groups (Mean difference= 1.91, SE= 0.51). Concerning baseline pain intensity, a main effect for group ($F_{(1, 80)} = 37.83$, $p < 0.0001$, $\eta_p^2 = 0.32$) and baseline pain intensity ($F_{(1, 80)} = 5.66$, $p < 0.02$, $\eta_p^2 = 0.07$) was present, but there was no interaction effect ($F_{(1, 80)} = 0.10$, $p = 0.75$). The low baseline pain groups spent less time thinking of their pain in comparison to the high groups (Mean difference= 1.27, SE= 0.53). More detailed results are shown in Table 4.

Table 4 Time spent thinking of pain: Planned contrasts for low and high scores on baseline parameters

	Group		Between group differences		
	Control	VR	$F_{(1, 80)}$	P-value	ES (η_p^2)
TSK					
Low	4.87 (0.51)	1.79 (0.50)	18.84	<0.0001	0.19
High	6.32 (0.56)	2.89 (0.57)	18.38	<0.0001	0.19
PCS					
Low	4.65 (0.48)	1.36 (0.49)	22.59	<0.0001	0.22
High	6.58 (0.53)	3.25 (0.52)	20.06	<0.0001	0.20
NPRS					
Low	4.81 (0.53)	1.71 (0.53)	17.03	<0.0001	0.18
High	6.24 (0.53)	2.81 (0.53)	20.89	<0.0001	0.21

Group means (SE) of the time spent thinking of pain during the exercises are presented. ES= Effect size, VR= virtual reality

3.4 Motivation and perceived harmfulness

As expected, the participants in the VR group were motivated to play the games. The median motivation score was 6.5/7 (IQR= 6 to 7, minimum score= 5/7). Further, participants in neither group perceived the exercises as harmful (VR group median score= 0 (IQR= 0 to 2), Control group median score= 0 (IQR= 0 to 3)) and the median harmfulness scores were not significantly different between groups (z= 1.29, p= 0.20). Therefore, both of our assumptions regarding the motivation and perceived harmfulness were confirmed.

4 Discussion

In this study, we used VR games to distract patients with CLBP during a single exercise session. Our aim was to investigate whether VR distraction had an influence on the pain intensity during and immediately after the exercises, and on the time spent thinking of the pain during the exercises. In addition, the effects of baseline pain intensity, pain-related fear and pain catastrophising on the effectiveness of VR distraction was assessed. Our results showed that, compared to a control condition, VR distraction significantly reduced the pain intensity during and after the exercises, and also the time spent thinking of the pain during the exercises. In both the VR and control group, participants with higher levels of pain-related fear and pain catastrophising at baseline experienced a higher pain intensity (or less decrease in pain) during and after the exercises, and spent an increased time thinking of pain. In both groups, a higher baseline pain intensity did not affect the differences in pain intensity during or after the exercises, but it did lead to an increased time spent thinking of pain. None of the baseline measures moderated the effectiveness of the VR distraction.

The analgesic effect of VR distraction in patients with chronic pain has predominantly been investigated in small and uncontrolled studies [29-34,37,38]. Overall, these studies have shown a reduction in pain intensity during and immediately after being immersed in a VR environment. By conducting a randomised controlled trial, we further extended these preliminary findings. A recent meta-analysis showed that distraction did not have an analgesic effect in patients with chronic pain when compared to a control condition,[2] which is in contrast to our study. Of importance, none of the studies included in this meta-analysis used VR as a means of distraction. Hence, VR games could potentially be more effective than other types of distraction, which is supported by research on acute procedural pain.[20] One of the suggested reasons for the effectiveness of VR distraction is the motivating character of the games. In the current study, participants were indeed motivated to play the games (minimum motivation score= 5/7). Motivation and goal pursuit have been proposed as important factors affecting the attention to pain. It is suggested that pain will have a less interruptive effect during an ongoing task when a person is motivated to fulfill that task or to achieve a particular goal that is not pain-related.[5,62] Based on our results, it would be worthwhile to further explore the role of motivation in attentional distraction of patients with chronic pain.

Patients with chronic pain have an attentional bias to pain, although the differences with healthy persons are small and depend on the methods used to measure it.[10,11] This selective attention to pain and the difficulty to disengage from it can be driven by pain-related cognitions and emotions, such as pain catastrophising and pain-related fear.[63-65] Therefore, it has been hypothesised that these factors may affect distraction induced analgesia, which is supported by some,[2,17,66,67] but not by all studies.[15,16] However, the results of our study do not confirm this hypothesis. This may be explained by the fact that we used a motivationally relevant distraction task. Indeed, Verhoeven et al.[5] showed that a neutral non-VR distraction task was effective for reducing experimentally induced pain in low, but not in high catastrophisers. In contrast, the level of pain catastrophising did not influence the analgesic effects of a motivationally relevant distraction task. Another explanation might be that the pelvic tilt exercises in the current study were not perceived to be harmful by the participants. Because pain especially captures attention when it is perceived as threatening,[12] the effects of VR distraction might potentially be attenuated by pain-related fear or catastrophic thinking if patients have to perform activities they perceive as harmful (e.g. lifting tasks).

Besides the threat value, also the intensity of pain influences its interruptive effect.[12] This has led to the hypothesis that distraction might be less effective for patients experiencing more severe levels of pain.[2] Few studies have investigated this in a chronic pain population, and the results are equivocal.[2,13] In our study, baseline pain intensity did not moderate the effectiveness of the VR-distraction. It should be noted, though, that the majority of the participants (85%) had mild to moderate levels of baseline pain. As such, only 30% of the patients categorised in the high baseline pain groups had a severe pain intensity at baseline (i.e. NPRS score of 7-8/10), which might have limited our ability to detect a moderating effect of this parameter.

A significant amount of research on the analgesic effects of (VR) distraction has been done in laboratory settings using experimentally induced pain, which may limit its ecological validity. To increase the clinical relevance of our study, we assessed the effects of VR distraction on the patients' clinical pain and we simulated clinical practice as closely as possible. All the tests were carried out in the hospital where participants followed their rehabilitation, participants performed clinically relevant exercises and we used a commercially available tool. In this respect, it is interesting that we obtained large effect sizes using a nonimmersive VR system. Immersion refers to the objective characteristics of the technological system,[50,68] such as the occlusion from the outside world or the presence of a high definition panoramic view. Although research has shown that the level of immersion is related to the magnitude of the analgesic effect of VR distraction,[50,69,70] studies also indicate that mainly the interactive aspect of VR games may be responsible for this analgesic effect.[71-73] As such, the latter might explain why the VR distraction in our study resulted in a significant reduction in pain, despite using a nonimmersive VR system.

To standardise the intervention, patients in the control group had to tilt their pelvis according to an auditory signal to ensure that they performed a similar number of repetitions compared to the VR group. As pelvic tilts can be painful for patients with CLBP, a temporal summation effect might occur if these movements are performed repetitively.[74,75] It could be argued that the auditory signal might have distracted participants in the control group. However, as shown by the meta-analysis by van Ryckeghem et al.,[2] non-VR distraction interventions do not have an analgesic effect in patients with chronic pain. More specifically, Goubert et al.[15] reported that a tone detection task to distract patients with CLBP during an active task did not reduce the pain during this activity. Therefore, it is unlikely that the auditory signals in the control group resulted in an analgesic effect.

Clinically, the aim of CLBP management is for patients to achieve their valued life goals.[76] Although different treatment strategies exist to obtain this aim, a common aspect is that they typically involve an active component, which may be embedded in a cognitive behavioral approach.[77] A major problem is that adherence to active therapies is low and the number of drop outs is high,[56,78] leading to suboptimal treatment results.[56,79,80] In this respect, patients with CLBP report that an important reason for this nonadherence is the experience of pain during activities or exercises.[56,81] As such, by reducing the pain intensity during exercises, VR games may have the potential to remove this barrier to engage in active therapies, thereby providing an avenue for obtaining better long term treatment results. Clearly, the latter needs further investigation.

Several limitations apply to this study. First, we assessed the pain immediately after the intervention, but it would be useful to also investigate the effects of VR distraction over a longer post-intervention period. This would allow to see whether a sustained analgesic effect is present or, conversely, to detect a potential delayed rebound effect of VR distraction. Second, the majority of the participants in this study had a mild to moderate baseline pain intensity. This might have limited the potential to detect a moderating effect of this parameter on the VR distraction. Therefore, future studies should specifically include patients suffering from more severe pain. Third, besides examining the moderating effects of pain-related fear and pain catastrophising on the VR distraction, it would be of interest to use more direct measures of attention to pain, such as the Pain Vigilance and Awareness Questionnaire[82] or experimental methods.[10,11] Finally, participants were familiar with pelvic tilt exercises and did not perceive them as harmful. Given that the threat value and novelty of a stimulus can influence the attention to pain,[12] future trials should investigate whether the analgesic effects of VR distraction are also present during unfamiliar and threatening situations. In addition, it is possible that pain-related cognitions and emotions might have a moderating effect during these type of activities.

In conclusion, this study provides evidence for the effectiveness of VR distraction to reduce the pain intensity during exercises for patients with CLBP. Baseline measures of pain intensity, pain-related fear and pain catastrophising did not moderate the analgesic effects of VR distraction. Future trials should further investigate the role of the motivational aspects of distraction and specifically explore whether analgesic effects are also present in patients with severe pain and during more threatening activities.

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Additional table 1 Regression models with continuous baseline measures for predicting the difference in pain during exercises

Baseline measure	factors	Estimate	SE	t-ratio	p	R² adj	ΔR² adj
Pain-related fear	Group [C]	-1.14	0.18	-6.53	<0.0001	0.28	
	TSK	-0.11	0.03	-3.39	0.0002	0.38	0.10
	Group*TSK	0.03	0.03	1.10	0.27	0.39	0.01
Catastrophising	Group [C]	-1.12	0.18	-6.21	<0.0001	0.28	
	PCS	-0.06	0.02	-3.13	0.002	0.36	0.08
	Group*PCS	0.01	0.02	0.4	0.52	0.36	0.00
Baseline pain	Group [C]	-1.11	0.19	-5.92	<0.0001	0.28	
	NPRS	0.19	0.13	2.26	0.14	0.29	0.01
	Group*NPRS	0.16	0.13	1.66	0.20	0.30	0.01

In the sequential multiple regression models, group was added in the first step, in the next step the baseline measure was added and in the final step the interaction between these two factors was added. The estimates (SE), t-ratio and p-values presented, are those for the full model. The difference in pain during the exercises (= dependent variable) was calculated by subtracting the pain intensity during the exercises from the baseline pain intensity. A positive value thus corresponds with an improvement in pain. Therefore, a negative estimate of a variable implies that this factor negatively influenced the improvement in pain intensity. Group [C]= Control group, NPRS= Numeric Pain Rating Scale, PCS= Pain Catastrophising Scale, TSK= Tampa Scale for Kinesiophobia.

Additional table 2 Regression models with continuous baseline measures for predicting the pain difference after the exercises

Baseline measure	factors	Estimate	SE	t-ratio	p	R² adj	ΔR² adj
Pain-related fear	Group [C]	-0.72	0.15	-4.82	<0.0001	0.14	
	TSK	-0.14	0.02	-5.54	<0.0001	0.37	0.23
	Group*TSK	0.02	0.02	0.99	0.32	0.37	0.00
Catastrophising	Group [C]	-0.68	0.16	-4.12	<0.0001	0.14	
	PCS	-0.05	0.02	-3.14	0.002	0.23	0.09
	Group*PCS	-0.002	0.02	-0.13	0.90	0.22	-0.01
Baseline pain	Group [C]	-0.67	0.17	-3.89	0.0002	0.14	
	NPRS	0.09	0.12	0.75	0.46	0.14	0.00
	Group*NPRS	0.16	0.12	1.34	0.18	0.15	0.01

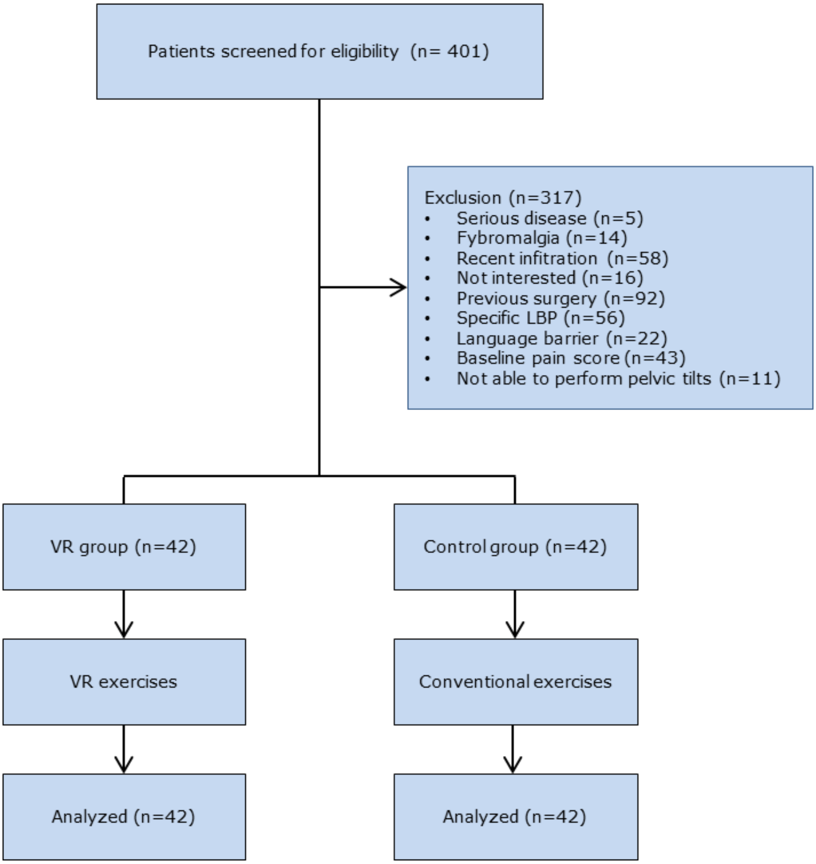
In the sequential multiple regression models, group was added in the first step, in the next step the baseline measure was added and in the final step the interaction between these two factors was added. The estimates (SE), t-ratio and p-values presented, are those for the full model. The difference in pain after the exercises (= dependent variable) was calculated by subtracting the pain intensity after the exercises from the baseline pain intensity. A positive value thus corresponds with an improvement in pain. Therefore, a negative estimate of a variable implies that this factor negatively influenced the improvement in pain intensity. Group [C]= Control group, NPRS= Numeric Pain Rating Scale, PCS= Pain Catastrophising Scale, TSK= Tampa Scale for Kinesiophobia.

Additional table 3 Regression models with continuous baseline measures for predicting the time spent thinking of pain

Baseline measure	factors	Estimate	SE	t-ratio	p	R² adj	ΔR² adj
Pain-related fear	Group [C]	1.68	0.26	6.39	<0.0001	0.30	
	TSK	0.12	0.04	2.82	0.006	0.35	0.05
	Group*TSK	-0.03	0.04	-0.75	0.46	0.35	0.00
Catastrophising	Group [C]	1.65	0.26	6.47	<0.0001	0.30	
	PCS	0.09	0.03	3.48	0.0008	0.39	0.09
	Group*PCS	-0.01	0.03	-0.29	0.77	0.38	-0.01
Baseline pain	Group [C]	1.61	0.26	6.24	<0.0001	0.30	
	NPRS	0.56	0.18	3.15	0.002	0.37	0.07
	Group*NPRS	-0.04	0.18	-0.20	0.84	0.36	-0.01

In the sequential multiple regression models, group was added in the first step, in the next step the baseline measure was added and in the final step the interaction between these two factors was added. The estimates (SE), t-ratio and p-values presented, are those for the full model. Group [C]= Control group, NPRS= Numeric Pain Rating Scale, PCS= Pain Catastrophising Scale, TSK= Tampa Scale for Kinesiophobia.

Additional figure 1 Flow of participants through the study



General Discussion

The overall scope of this PhD project was to expand our knowledge on how technology can be used to remove barriers to, or to support important aspects of exercise therapy for patients with chronic nonspecific low back pain. We focused on three main aspects:

1. Integrating technological support into a tailored home exercise programme.
2. Providing postural feedback to improve lumbopelvic movement control.
3. Attentional distraction with virtual reality games for reducing pain.

In this general discussion, I will first summarise the results of the different studies that we conducted. In a second part, I will critically review our results and discuss some important methodological considerations. Next, the clinical implications of our research are discussed, and finally, recommendations for future research are made.

1 Summary of study results

1.1 Chapter I

Our **Systematic Review** (Study 1) showed that technology-supported exercise therapy (TSET) is not more effective than other interventions or a placebo/waiting list to improve pain, disability or quality of life, even when only more recent trials were considered. In addition, when the technological support was the single difference between interventions, no between-groups differences could be found. A standard therapy combined with a TSET-programme led to larger improvements in pain and disability compared to a standard therapy alone. However, when TSET was added to a standard therapy that was already effective, the additional benefits of TSET were less clear. The lack of benefit from technological support may possibly be explained by the fact that technological support was not integrated into a programme containing individually tailored, functional and home exercises.

To assess whether it is possible to implement technology (i.e. serious games and sensor-based postural feedback) into such an exercise programme, we conducted a **Feasibility Study** (Study 2). Ten patients with chronic nonspecific low back pain (CNSLBP) and an underlying movement control impairment were recruited. All participants received an exercise programme that was based on the same principles of movement control training, but which was tailored to the individual patient.[1] The technology-supported exercises were integrated into functional activities and technological support was provided at the rehabilitation centre and at home. Our study showed that it is feasible to support a functional exercise programme with technology for patients with CNSLBP, both in a supervised and a home environment. Participants found the intervention credible and remained motivated throughout the study. In addition, no serious adverse events were reported. However, the time needed to set up the games was a barrier for home use and participants would have found it useful to have received postural feedback during daily life activities. In addition, we were not able to measure the adherence to home exercises, which was an important limitation of this study.

1.2 Chapter II

First, we conducted a **Reliability Study** (Study 3) in healthy participants. We investigated during which functional movement control tasks we could assess lumbopelvic kinematics reliably and with sufficient agreement. We were mainly interested in establishing the minimal detectable change between two measurements (i.e. measurement error), as this would be essential for our intervention study (Study 4). Four different movement control tasks were assessed: waiter’s bow (WB), stance-to-sit-to-stance (SIT), lifting a box from the floor (LIFT) and placing a box on an overhead shelf (OVERH). The maximal deviation from the starting position in the lumbar spine and hip were calculated for each task (i.e. range of motion expressed in degrees). Both the within and between session reliability of the WB and LIFT task were substantial (ICC range= 0.89–0.96), SIT was moderately to substantially reliable (ICC= 0.69-0.92) and OVERH was fairly to moderately reliable (ICC= 0.40-0.67). Because of the substantial reliability and acceptable measurement error of WB and LIFT (~5° in the lumbar spine, ~10° in the hip), these two movement control tasks were used in our intervention study.

In this **Intervention Study** (Study 4), we investigated whether **sensor-based postural feedback** was more effective than feedback from a mirror or no feedback to improve lumbopelvic movement control in patients with CNSLBP. In addition, we assessed whether patients with CNSLBP were equally capable of improving lumbopelvic movement control compared to healthy persons. During the intervention, participants practised the WB during 3 sets of 6 repetitions while receiving their designated form of feedback (i.e. from sensors, a mirror or no feedback). Our results showed that sensor-based feedback was significantly more effective than feedback from a mirror and no feedback to improve lumbopelvic movement control performance (measured with the WB) and motor learning (measured with the LIFT task). The between groups differences were also larger than the measurement error, except for the hip joint during the LIFT task. Patients with CLBP were equally capable of improving lumbopelvic movement control compared to healthy persons.

1.3 Chapter III

Finally, we conducted an **intervention study** (Study 5) in patients with CNSLBP to assess whether **virtual reality (VR) distraction** had an analgesic effect during and after exercises, and whether it influenced the time spent thinking of pain during the exercises. Furthermore, we investigated whether levels of baseline pain intensity, pain catastrophising and pain-related fear moderated the effects of VR distraction. Participants in the intervention group played two VR games which had to be controlled by pelvic tilts. Participants in the control group tilted their pelvis according to an auditory signal. Our results showed that participants in the VR group experienced significantly less pain during and immediately after the exercises, and they spent significantly less time thinking of their pain compared to the control group. The effect sizes (Cohen's *d*) were large, an ranged between 0.85 and 1.31. Baseline levels of pain intensity, pain catastrophising and pain-related fear did not moderate the effectiveness of the VR distraction.

Table 1 Overview of the main study findings

Ch.	Study		Main findings
	N°	Type	
I	1	Systematic Review	• A standard therapy and TSET is more effective than TSET alone for improving pain, disability and quality of life. TSET is equally effective compared to other interventions, a waiting list or placebo for improving these outcomes. • Very few studies integrate technological support during individually tailored, functional or home exercises.
	2	Feasibility	• It is feasible to provide postural feedback during individually tailored movement control exercises, both in a supervised and in a home environment. • Patients found this approach credible and they remained motivated during a long-term (18-week) intervention. • The time to set up the games was a barrier to use the technological support. Participants would have preferred a system that could be used during daily life.
II	3	Reliability	• The waiter's bow and lifting task showed substantial within and between session reliability (ICC range= 0.89-0.96). The stand-to-sit-to-stand task was moderately to substantially reliable (ICC range= 0.69-0.92). Overhead lifting was fairly to moderately reliable (ICC range= 0.40-0.67). • Based on the substantial reliability and acceptable agreement (minimal detectable change of lumbar spine ~ 5-6°), the waiter's bow and lifting task were selected to be used in our sensor-FB study.
	4	Sensor-FB	• Sensor-based FB was more effective than feedback from a mirror or no feedback to improve lumbopelvic movement control. Both the performance of the waiter's bow, as well as the transfer effect to the lifting task improved significantly more in the sensor-group as compared to the other groups. • Patients with CLBP and healthy persons were equally capable of improving lumbopelvic movement control. • Participants did not become dependent on the feedback, as no deterioration in performance was present between the last practise repetition and the post-intervention assessment. • About 2/3 of the patients in the sensor group had an improvement that was larger than the minimal detectable change. After the intervention, 8 out of 9 'responders' in the sensor group performed the waiter's bow with less than 5° of lumbar ROM.
III	5	VR distraction	• Patients in the VR group experienced significantly less pain during and immediately after the exercises, and they thought significantly less about their pain during the exercises. Effect sizes were large (ES range= 0.85-1.31). • Baseline levels of pain-related fear, pain catastrophising and pain intensity did not moderate the effects of VR distraction.

FB= feedback, TSET= technology-supported exercise therapy, VR= virtual reality.

2 Critical review and methodological considerations

The results presented in this dissertation should be interpreted in light of various methodological limitations. The most important ones will be discussed below.

2.1 Type of technology

Only one type of technological system was used in this PhD project. We used the ValedoMotion (version 1.2, Hocoma, Switzerland) for our feasibility, reliability and sensor-based feedback studies (i.e. Studies 2-4). The ValedoPro (Hocoma, Switzerland), which is an updated version of ValedoMotion, was used in our VR distraction study (study 5). It could be argued that using only one type of technology is a limitation of this project. Potentially, the results of our studies would have been different with other technologies. However, we chose to use Valedo because of two main reasons. First, the overall aim of this PhD project was not to compare different technologies to each other, but to investigate whether it was possible to support important aspects of, or to remove barriers to exercise therapy. In our opinion, the Valedo system was best suited to investigate these research questions. Second, using Valedo was also a pragmatic choice. The more specific reasons for choosing Valedo are described below.

- *LBP specific system*: The Valedo was developed specifically for LBP rehabilitation. This is in contrast to other frequently used active videogame systems, such as the Microsoft Kinect, Nintendo Wii or Sony Playstation.[2] The latter systems are not capable of providing specific postural feedback during lumbar movement control exercises (Studies 2 and 4). Moreover, the games are not suited to support thoracolumbar dissociation or proprioceptive exercises (Study 2). In contrast, the ViMove system (DorsaVi, Melbourne, Australia) has also been specifically developed for LBP rehabilitation. Similar to Valedo, it works with movement sensors that have to be mounted to the lumbar spine, which can provide postural feedback to the patients and measure lumbar kinematics.[3,4] The advantage of the ViMove over the Valedo System is its capability of recording paravertebral muscle activity using surface electromyography. This could have been useful during our sensor-based feedback study (Study 4), as muscle activity patterns can be considered as an aspect of movement control. However, the ViMove system does not contain active games for LBP, which were essential for our feasibility and VR-distraction studies (Studies 2 and 5).

- *Commercially available*: This availability enhances the ecological validity of our results. Therapists are able to buy the system and use it in the same way as in our intervention studies. In contrast, some studies have used custom made systems, such as SnowWorld, which has been studied extensively for distracting patients with burn wounds from their pain.[5,6] Designing specific technological systems is an expensive and long iterative process, and could be considered as a research project on its own. Therefore, using an already available tool was essential for this project.
- *Validated measurement tool*: At the beginning of this project, the ValedoMotion had already been validated as a tool to measure lumbopelvic kinematics.[7,8] In addition, the ValedoMotion was able to assess these kinematics while providing postural feedback. Given our interest in improving lumbopelvic movement control (Study 4), this system was very well suited.
- *Portable system*: We tested participants at different locations. This would not have been possible with systems that are fixed to a certain location (e.g. CAREN-system).

2.2 Effectiveness of technology-supported exercise therapy

2.2.1 Update of the systematic review

The conclusions of a systematic review can become outdated after a few years, as the most recently published studies are not included. Therefore, I updated the results of our systematic review by repeating the original search in the Pubmed database in April 2019. Five additional papers were retrieved that fulfilled the inclusion criteria of our systematic review (see Table 2 for details).[9-13] All of these studies were performed in a CNSLBP population. Four trials compared technology-supported exercise therapy (TSET) to a control group receiving no treatment or the simple advise to continue normal activities.[9-12]

One study compared a standard therapy and TSET to a standard therapy alone.[13]

In only one trial[10] comparing TSET to no intervention, TSET led to clinically important differences in pain (i.e. >2 points on the VAS or NPRS)[14,15] and disability (i.e. >10% on the ODI; >3 to 5 points on the RMDQ).[14,16] None of the three other studies showed clinically meaningful differences in pain or disability between TSET and a no-intervention control group.[9,11,12] One study showed that adding a Nintendo Wii programme to a standard therapy did not lead to a significantly larger reduction in pain compared to a standard treatment alone.[13] Therefore, these updated results strengthen the conclusions of our systematic review, showing that in the majority of studies, TSET is not superior in a clinically meaningful way compared to a control group receiving no intervention. Furthermore, these results also confirm our conclusions that supporting exercises with more recently developed technologies does not lead to better treatment outcomes compared to support from older technologies.

Table 2 Studies included in the update of the systematic review

Study	N	TSET	Results[a]
Arampatzis, 2017	40	Patients were in a semiseated position and had to resist external perturbations to the trunk that were given via a harnas. 26 sessions, 1.5h each, 2x/week	Within group differences Pain (VAS): TSET= -0.96; Co= -0.29 (*S*)
Kaeding, 2017	39	WBV training at workplace. 2-3x/week, 15’ per session, during 3 months.	Within group differences Disability (RMDQ): TSET= -1.5; Co= 0.3 (*S*) Disability (ODI%): TSET= -4.5; Co= 1.2 (*S*) QoL (SF36, Physical): TSET= 3.4; Co= -3.9 (*S*) QoL (SF36, Mental): TSET= 4.1; Co= 0.3 (*NS*)
Letafatkar, 2017	30	Sensorimotor/movement control training on HUBER machine. Participants stood on a platform that rotated and oscillated while participants had to maintain their posture. Participants had to push/pull handles of the machine to keep their position and also received visual feedback.	Within group differences Pain (VAS): TSET= -4.3; Co= 0.5 (*S*) Disability (RMDQ): TSET= -6.1; Co= 0.1 (*S*)
Zadro, 2019[b]	60	Nintendo Wii Fit U games at home without supervision. Games included flexibility, body-weight transfer and aerobic exercises. 8 weeks, 3x/week, 60’ per session.	Between groups differences Pain (NPRS)= 1.07 (in favour of TSET, *S*) Disability (RMDQ)= 0.85 (in favour of TSET, *NS*)
Monteiro-Junior, 2016[b,c]	34	Nintendo Wii Fit exercises, including yoga, balance and strength games. Standard therapy consisted of strengthening exercises for the spine and lower limbs. 8 weeks, 3x/week, 90’ per session.	Between groups differences Pain (VAS)= effect size of 0.1 (*NS*)

NPRS= Numeric Pain Rating Scale; ODI= Oswestry Disability Index; RMDQ= Roland Morris Disability Questionnaire; TSET= Technology-supported exercise therapy; VAS= Visual Analog Scale; WBV= Whole body vibration

[a] Results: all results are expressed in the values of the scale used to assess the outcome. An improvement in pain and disability is indicated by a negative value. An improvement in quality of life corresponds with a positive value. Between groups differences are presented when available, otherwise, within group differences are given. (*S*)= significant between groups difference; (*NS*)= non-significant between groups difference. All results were obtained immediately after the intervention.

[b] Only older participants were recruited. Mean age in both studies was 68 years.

[c] Monteiro-Junior et al. compared a standard therapy and TSET vs a standard therapy alone.

2.2.2 The additional value of technological support

In none of the newly retrieved studies, technology was the single difference between the TSET and the control group. As such, the conclusion of our original systematic review, being that technological support has no additional benefit, remains unchanged. However, this conclusion is based on only five studies, mainly using a very narrow approach to exercise therapy. Therefore, these conclusions need to be interpreted with caution.

Another aspect to consider is that study outcomes have only been measured at the end of the intervention. As shown by our own study, sensor-based postural feedback led to rapid improvements in movement control, while this was not the case when feedback from a mirror was provided (Study 4). Potentially, these quicker improvements in movement control might result in faster reductions in pain or disability. However, this is speculative as it has not been investigated whether improvements in movement control mediate the treatment outcomes after an exercise programme for patients with CLBP. To investigate whether TSET leads to quicker improvements than conventional exercise therapy, randomised controlled trials (RCTs) with measurements at multiple time points are necessary. Clearly, this is very time-consuming and not always easy from a practical point of view. As an alternative, single-case experimental designs can be used, especially when kinematic measures of movement control need to be obtained at multiple time points.[17,18] Although the level of evidence is lower than that of an RCT, these single-case designs would allow to identify how change unfolds throughout the intervention.[17]

Even when technological support does not increase the treatment efficacy, it can still be useful by improving the cost-effectiveness or the access to care. For example, when patients are able to practise more independently and need less supervision, it can lower the treatment costs. Furthermore, if technological support would lead to a quicker improvement, LBP-related costs might be reduced (e.g. less sick leave). Finally, telerehabilitation may be a solution for less mobile patients or for those living in remote areas.[19,20] On the other hand, technology might increase the treatment costs when specific systems are necessary, especially when they have to be operated by a therapist (e.g. real-time ultrasound imaging[21]). A cost-effectiveness calculation has only been performed of the study by Kent et al.[3,22] In this study, a standard therapy combined with TSET was compared to a standard therapy alone in a mixed population of patients with subacute and chronic LBP.[3] The standard therapy consisted of guideline based care, including advice, medical treatment and physical therapy as deemed essential by the treating clinicians. The TSET consisted of individually tailored movement control exercises that were supported by postural feedback from motion sensors (ViMove). This study showed that the costs of providing the TSET intervention were higher than those of the standard therapy because of the costs related to the technological system. Nonetheless, the standard therapy combined with the TSET intervention was significantly more cost-effective than the standard therapy alone, mainly because the participants in the TSET group became more productive (i.e. employment-wise) over the 12 month follow-up period.[22] The reason for the increased cost-effectiveness of the TSET was thus related to the better clinical effect in the TSET-group.[22] It should be noted, though, that we cannot be sure that the clinical improvements, nor the enhanced cost-effectiveness can be attributed to the technological support. The same results might have been obtained if tailored movement control exercises without technological support were added to the standard treatment.

2.2.3 Conclusions

The main conclusions of our systematic review remain the same, and can be summarized as follows:

- There is no evidence that TSET leads to better clinical outcomes than conventional exercises.
- There is a lack of studies that integrate technological support into an individually tailored and functional exercise programme including home exercises.
- To assess the additional effect of technology, RCTs are necessary where the technological support is the single difference between both interventions.
- The benefit of technological support should be assessed from different perspectives.

2.3 Feasibility of tailored technology-supported exercises

2.3.1 Critical review of our results

It has been suggested that one of the advantages of technological support is its ability to increase the motivation to exercise, thereby enhancing the adherence.[9,23] The results of our feasibility study did indeed show that participants remained motivated throughout the intervention, however, we were not able to collect self-reported adherence to the home exercises. This was due to the fact that participants did not properly complete the exercise diaries. While participants reported that the games were fun to play and the postural feedback helped them to perform their exercises more correctly, a majority of the participants also mentioned that the time needed to set up the Valedo system was a barrier to use it. In their pilot trial, Hügli et al. showed that self-reported adherence to home exercises was not higher when patients with (sub)acute LBP were supported by feedback from the Valedo.[24] In the study by Zadro et al., patients with CLBP who were over 55 years old completed an 8-week home based Nintendo Wii fit exercise programme that was supported by regular telephone calls by the investigators.[9] The adherence rates were high (85% of exercise sessions performed), and larger than usually reported in studies using conventional home exercises.[25-27] The mean exercise time per session was 42 minutes (~ 70% of recommended time) in the study by Zadro et al., while this was 9 minutes (~ 50% of recommended time) in the study of Hügli et al.[24] Potentially, the high adherence rates in the study by Zadro et al., can be explained by the fact that only 20% of the participants was employed.[9] Indeed, from our feasibility study, it became clear that for the participants who were employed, the time to set up the Valedo system and the inability to practise during daily life activities were barriers to use system. In contrast, participants who were on sick leave or retired did not mention that a lack of time was a barrier to exercise.

The results of our feasibility study suggest that providing tailored movement control exercises supported by sensor-based postural feedback leads to clinically relevant improvements in pain and disability. Clearly, given the absence of a control group and the small number of participants, these results need to be interpreted with care and no conclusions can be drawn regarding the additional benefit of the technological support. Nonetheless, these positive results are interesting, since other studies that simply provided standard active video games with a Nintendo Wii did not report relevant reductions in pain and disability within the intervention group.[9,28] One trial that used Nintendo Wii exercises did show clinically important improvements.[29] However, the results of this study can be questioned given the unrealistically high scores on the baseline measures (e.g. Roland Morris Disability Questionnaire mean score= 18.6 (SD= 2.8)) and atypical large improvements in the intervention group (e.g. improvement in VAS score for pain from 7.0 (SD= 0.9) to 2.2 (SD= 1.1)). Moreover, the study by Kent et al. showed that a standard therapy enhanced with tailored movement control exercises supported by sensor-based feedback, led to larger improvements in pain and disability than a standard therapy alone.[3] In contrast, adding Nintendo Wii exercises to a standard rehabilitation had no additional benefit over a standard rehabilitation alone.[13] These results seem to indicate that simply providing nonspecific active gaming exercises is not effective for patients with LBP. In contrast, the preliminary evidence based on our feasibility trial and the study by Kent et al.,[3] does support the idea that technological support should be integrated into an individually tailored approach to exercise therapy.

2.3.2 Methodological considerations

In our feasibility study, the ValedoMotion was used to support the exercises, as the (newer) ValedoPro was not yet available at that moment. Although the features of both systems are comparable, the sensor calibration with the ValedoPro is much easier and quicker than with the ValedoMotion system. Therefore, the time needed to set up the system may not have been such an important barrier if we could have used the ValedoPro. This highlights one of the difficulties when conducting research with technology. By the time a study is finished, a new and improved version might be available.

2.4 Reliability and agreement of functional movement control tasks

Prior to our randomised trial investigating the effectiveness of sensor-based postural feedback, we conducted a reliability and agreement study. The main goal of this study was to establish the measurement error between two evaluations of functional movement control tasks. This was deemed important as we planned to use a selection of these tasks in our intervention study to measure the improvements in movement control between baseline and post-intervention assessment. It should be noted, though, that we only conducted our reliability study in a healthy population. This can be considered as a limitation, because we also included patients with CLBP in our intervention study. In general, it is assumed that reliability and agreement coefficients are population specific.[30] Therefore, it can be argued that it would have been more accurate to have also conducted a reliability study in a CLBP population fulfilling the inclusion criteria of our intervention study.

However, the available literature shows that (between session) reliability and agreement coefficients of lumbar spine kinematics during active movements do not significantly differ between healthy persons and patients with CLBP.[31-33] Although this observation might be at odds with the general assumption of population specificity, there are good arguments to explain the similarity of these coefficients between healthy persons and patients with CLBP. One of the stated reasons why reliability and agreement coefficients can be population specific is because of the fluctuations in clinical status of the patient.[34] Regarding our study, this could be a valid argument, since it has been shown that the clinical status of patients with CLBP (e.g. the level of pain intensity) may affect lumbar movement patterns.[35,36] Therefore, significant changes in this status between the test and retest session could result in a less consistent performance on the movement tasks, and thus in less reliability and agreement. However, research shows that the clinical status of most patients with CLBP who are not receiving treatment is quite stable over time, even when this status is measured on a day-to-day basis.[17,37,38] Therefore, these minor fluctuations might not be large enough to affect movement patterns. A second argument why reliability and agreement coefficients might differ between healthy persons and patients with CLBP are the differences in movement parameters, such as ROM and movement speed, that are typically observed between these two populations.[35,39] However, reliability and agreement are related to movement variability, rather than to absolute measures of movement (e.g. maximal amount of ROM).[40] Basically, reliability depends on the between-subjects variability, relative to the within-subjects variability (and error).[40] When the variability between subjects is large and the within-subject variability is low, the reliability will increase. In this respect, some studies have shown that the within-subject movement variability measured with spinal kinematics is actually smaller in patients with CLBP,[41-44] as compared to healthy persons, although opposite findings have also been reported.[45] Regarding between-subject variability, a recent study by Laird et al., investigating lumbopelvic kinematics during forward bending, showed that between subject variability is larger in patients with CLBP, compared to healthy subjects.[4] However, little research has been done on between subject variability, so strong conclusions cannot be drawn. Taken together, the available evidence does not show that the within-subject movement variability in patients with CLBP is larger compared to healthy subjects (rather the opposite), or that the between subject movement variability is smaller in patients with CLBP. This may explain the similarity in reliability and agreement coefficients between healthy persons and patients with CLBP.

Despite the latter, we should be prudent to extrapolate the findings from other papers to our own study, because there are differences in the specific movements that were tested or the equipment that was used to measure the kinematics. In this respect, it is interesting that Bauer et al. did not find a difference in within-subject movement variability between healthy persons and patients with CLBP during a waiter’s bow.[36] Of importance, Bauer et al. also used same device (i.e. ValedoMotion sensors) as in our studies to assess the kinematics.

To further investigate potential differences in reliability and agreement coefficients between healthy persons and patients with CLBP, I analysed the baseline kinematic data from our sensor-based feedback study (Chapter II, Study 4). During this baseline assessment, participants first performed five repetitions of the lifting task, after which they performed five repetitions of the waiter’s bow. This methodology was identical to our reliability study concerning number of repetitions and set-up (e.g. instructions, weight of the box, height of stool that had to be touched). The only differences were that during the reliability study, participants were allowed to familiarise with the movements, and that they performed the four tasks in a randomised manner. During the sensor-based feedback, no familiarisation was allowed, and only the lifting task and waiter's bow were performed in a fixed order.

Using the baseline data from our sensor-based feedback study, I calculated within session intraclass correlation coefficients (ICCs) and standard errors of measurement (SEMs) in an identical way to our reliability study. ICCs and SEMs were obtained for healthy persons and patients with CLBP, and for different sample sizes per group (N= 20, N= 30, N= 40 and N= 50). The results show that the ICCs are very similar when comparing healthy persons and patients with CLBP (see Tables 3 and 4). Moreover, the 95% CIs of ICCs for a given task, joint and sample size are overlapping. It is also clear that the measurement errors between both populations are highly similar. In fact, for the lifting task, the SEMs are even slightly smaller in the CLBP group. Furthermore, both the ICCs and SEMs remain very stable when different sample sizes are used. It should be clear, though, that the secondary analysis of the baseline data from the sensor feedback study only pertains to within session reliability and agreement. As such, based on these results, no conclusions can be drawn regarding between session coefficients.

Table 3 Within session reliability and agreement of baseline measures of Waiter's Bow

		Healthy persons			Patients with CLBP		
		ICCw	95%CI	SEMw	ICCw	95% CI	SEMw
LS	N=20	0.90	(0.82-0.95)	2.3	0.89	(0.80-0.94)	2.4
	N=30	0.91	(0.86-0.95)	2.4	0.86	(0.78-0.92)	2.5
	N=40	0.91	(0.86-0.95)	2.6	0.88	(0.82-0.93)	2.3
	N=50	0.89	(0.84-0.93)	2.6	0.89	(0.83-0.93)	2.1
Hip	N=20	0.94	(0.88-0.97)	3.8	0.88	(0.77-0.94)	3.5
	N=30	0.94	(0.90-0.97)	3.5	0.92	(0.87-0.96)	3.9
	N=40	0.93	(0.89-0.96)	3.8	0.91	(0.95-0.95)	3.8
	N=50	0.92	(0.89-0.95)	3.6	0.91	(0.87-0.95)	3.6

ICCw= Intraclass correlation coefficient within session, LS= lumbar spine, SEMw= Standard error of measurement within session.

Table 4 Within session reliability and agreement of baseline measures of Lifting Task

		Healthy persons			Patients with CLBP		
		ICCw	95%CI	SEMw	ICCw	95% CI	SEMw
LS	N=20	0.93	(0.88-0.97)	2.4	0.98	(0.96-0.99)	1.5
	N=30	0.93	(0.89-0.96)	3.0	0.96	(0.94-0.98)	1.7
	N=40	0.93	(0.90-0.96)	2.9	0.95	(0.93-0.97)	1.9
	N=50	0.93	(0.90-0.96)	2.9	0.94	(0.91-0.96)	2.0
Hip	N=20	0.94	(0.92-0.97)	3.3	0.96	(0.92-0.98)	3.0
	N=30	0.93	(0.89-0.96)	3.9	0.95	(0.91-0.97)	2.9
	N=40	0.93	(0.90-0.96)	3.8	0.95	(0.92-0.97)	3.0
	N=50	0.92	(0.88-0.95)	4.0	0.95	(0.92-0.97)	2.9

ICCw= Intraclass correlation coefficient within session, LS= lumbar spine, SEMw= Standard error of measurement within session.

In summary, we have shown that both the literature and the analyses of our own data suggest that the reliability and agreement of lumbar kinematics do not significantly differ between healthy persons and patients with CLBP. We also provided a logical explanation for the latter. Notwithstanding these arguments, results from other papers cannot simply be extrapolated to our own study, and the analyses of our baseline data only inform us about within session and not about between session coefficients. As such, the fact that we conducted a reliability and agreement study in a healthy population can be considered as a limitation, since we also included patients with CLBP in our intervention study.

2.5 Movement control and sensor-based postural feedback.

2.5.1 Critical review of our results

In our study, we showed that it was possible to improve lumbopelvic movement control during a single exercise session with sensor-based postural feedback. Two other studies used a similar approach, and also reported that lumbopelvic movement patterns of patients with CLBP could be changed immediately after a single intervention session.[46,47] In both of these trials, the feedback during the movement control training was provided by a therapist and consisted of verbal instructions, manual guidance and demonstrations. Furthermore, these studies assessed whether it was possible to change the patients' *preferred* movement pattern. This means that at baseline assessment, participants were asked to perform a task in their habitual way. In contrast, participants in our study already received the instructions to maintain the lumbar curvature during the baseline tasks. Notwithstanding the differences, together with our trial, these studies show that movement control of the lumbar spine during analytical[46] and functional tasks[47] can be improved immediately after a single training session. Based on these results, it would also be of interest to compare the effectiveness of sensor-based postural feedback to a therapist-led intervention.

Although we showed that sensor-based feedback was effective for improving lumbopelvic movement control, not every participant with LBP responded to the intervention. For the waiter's bow, 9 out of 14 (64%) participants in the sensor-group had a decrease in lumbar ROM that was larger than the measurement error (1 additional person almost reached this threshold). In the control and mirror group, respectively 1 (7%) and 4 (27%) participants reached improvements larger than the measurement error. After the intervention, 8 out of 9 'responders' in the sensor group performed the waiter's bow with less than 5° of lumbar ROM (0° being a perfect performance). Various reasons might be responsible why approximately one third of participants in the sensor-group did not improve. First, although we aimed to provide easy-to-understand feedback, we cannot rule out that the visual feedback from the sensors (i.e. the stickman) may have been less intuitive or too difficult to interpret for non-responders. Because high levels of attention to the practised task are required in the early stages of skill acquisition,[48] the motor learning process may have been attenuated if too much attention had to be directed towards the interpretation of the feedback. Potentially, a different visual representation or a different type of feedback (e.g. vibrotactile[49]) could have been more effective for the non-responders. The latter would be worthwhile to investigate in future research. A second reason might be that non-responders may have lacked the basic movement skills to adjust their spinal curvature via pelvic tilts. To limit the influence of previous experience, participants were excluded if they had performed movement control training in the year preceding the trial. As such, the movement control tasks in our study might have been too complicated for these individuals.

2.5.2 Methodological considerations

An a-priori determined threshold of 10° of lumbar range of motion (ROM) during the baseline movement control tasks was used as a performance-related inclusion criterion. The 10° ROM threshold was based on a small pilot trial (n= 8, unpublished data) we conducted prior to the main study. In this pilot trial, participants (healthy and CLBP) performed the waiter's bow and lifting task while we measured lumbopelvic kinematics and recorded the movement control tasks with a digital video camera. The moment when participants were unable to maintain their lumbar curvature, as assessed by inspection of the videos, corresponded with 10° of lumbar flexion. Importantly, this threshold was larger than the measurement error. From a clinical point of view, the movement control exercises we used in our study would be provided to patients with an underlying flexion-related movement control impairment.[50,51] Although the threshold for inclusion was based on empirical data, we did not perform a full clinical assessment to establish the diagnosis of a flexion-related movement control impairment.[50-52] Potentially, this might have influenced our results. On the one hand, persons with a poor control might need more training, on the other hand, they also have a larger potential for improvement. Our results support the latter, as they showed that a poor performance on the baseline tasks predicted a larger improvement in movement control. This is in line with the results from the previously mentioned studies that used a single session of therapist delivered feedback (see paragraph 2.3.2).[47,53]

Participants in our study only performed 3 sets of 6 repetitions. The number of repetitions was limited to prevent the development of fatigue and an increase in pain, as these aspects may influence movement patterns.[54-56] The results of the post-intervention questionnaires indicated that no fatigue or pain increase were present. It is possible that the improvements in movement control would have been larger with more time to practise. However, looking at the graph (Fig. 1) depicting the evolution of lumbar ROM throughout the intervention in the sensor group, it is clear that the improvements are mainly present during the first set of repetitions, after which there is a plateau phase. To illustrate this, after 6 repetitions, the average improvement in lumbar ROM of the responders in the sensor group of CLBP patients was 61.3% (SD= 22.7%). After 12 and 18 repetitions, the respective improvements were 72.8% (SD= 11.8%) and 69.3% (SD= 11.2%). Therefore, it is unlikely that participants would have made any further improvements if they had performed an extra set of repetitions without additional instructions.

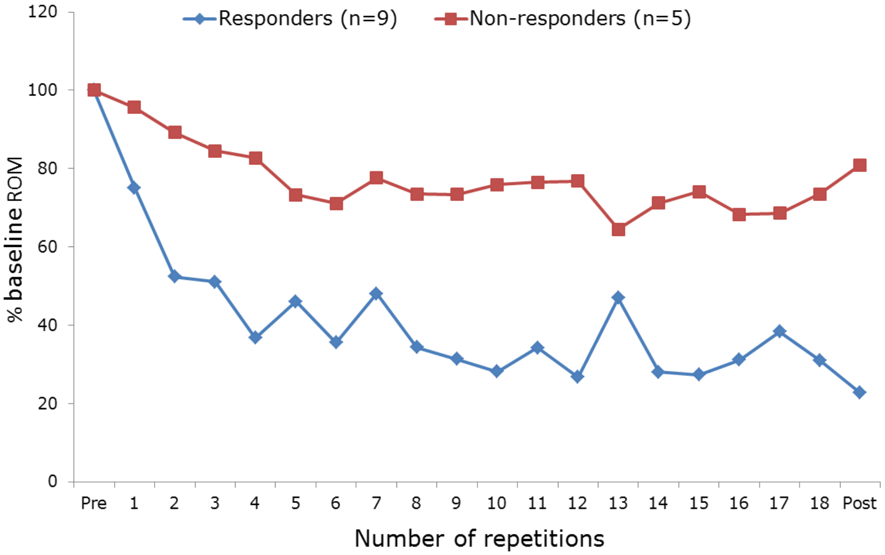


Fig. 1 Evolution of the lumbar ROM during the practise of the waiter's bow for the sensor-group in patients with CLBP. Data are shown as a percentage of the baseline ROM. Pre= baseline measurement, Post= post-intervention measurement.

Using a single intervention session might also have increased the observed difference between the sensor and the mirror groups. We hypothesised that the lack of improvement in the mirror group might be explained by the difficulty for patients to visually detect changes in the lumbar curvature during the waiter's bow. Potentially, if participants would have received a longer teaching period or multiple sessions of feedback from a mirror, they might have achieved similar improvements than participants in the sensor groups. Therefore, between group differences might be reduced or not be present after multiple training sessions. Even if this would be the case, however, the fact that sensor-based postural feedback leads to quicker improvements in movement control than feedback from a mirror, could still be considered as a clinically relevant result.

An essential part of motor learning is the transfer of learned movement skills from trained to untrained tasks,[57] as it is impossible to practise each possible movement. In our study, this transfer was assessed with a lifting task. There were various reasons why we chose this particular task:

- *Acceptable measurement error*: In our reliability study (Study 3), we had shown that the lifting task could be assessed with excellent reliability and sufficient agreement. The latter is essential for measuring the improvement between baseline and post-intervention performance.
- *Clinically relevant*: When teaching patients new movement skills, therapists often use the concept of task segmentation, which refers to the practise of an individual component before practising the whole task.[1] The lifting task contains the two main aspects of the waiter’s bow, being the performance of a hip flexion movement while maintaining the spinal curvature.
- *Theoretical background*: Two main theoretical frameworks have been put forward to explain the concept of skill transfer.[58] The identical elements theory states that transfer is positively associated with the number of elements that two skills share in common (e.g. movement characteristics). The transfer-appropriate processing theory postulates that transfer is correlated to the similarity in cognitive processes between the skills (e.g. attention, decision making). As such, in order to observe a potential transfer effect after a short training period, such as the one in our study, the practised and the transfer task had to share similarities regarding skill components and cognitive processes.

Apart from the transfer, also the long-term retention of newly acquired movement skills is important during motor learning.[48,57] This was not assessed in our study, nor in the studies using a single session of therapist feedback.[46,47] Besides these short interventions, more extensive clinical trials (6 to 24 treatment sessions) that used movement control exercises primarily to reduce pain and disability, also showed that these interventions improved movement control.[24,59-62] However, the movement control assessment was performed immediately post-intervention and not during long-term follow up. In addition, movement control was only assessed during standard analytical movement control tasks, and except for one study that used kinematic measurements,[62] all the evaluations were done on visual inspection and without assessor blinding, which may have created a bias. Furthermore, none of these studies investigated whether improvements in movement control were related to reductions in pain and disability. Therefore, the following questions remain unanswered:

- Do movement control exercises improve cognitive movement control in the long term? That is, do they improve the ability to cognitively coordinate movement at a specific joint or region in a particular movement direction?[63]
- Do movement control exercises change preferred movement patterns in the long term? That is, do they change an individual's habitual movement patterns?[63]
- Do improvements in cognitive movement control or changes in preferred movement patterns mediate reductions in pain and disability?

A final aspect is that we only used the maximal deviation from the starting position as a measure of movement control, which could be considered as a rather reductionist approach. Other parameters, such as muscle activity patterns or timing of inter-joint coupling can also be important.[4,39,64-66] For example, a low load task such as the waiter's bow should ideally be performed with relatively low levels of muscle activity and without strong co-activation of the abdominal muscles (i.e. bracing).[1,67] Because we did not obtain electromyographic measurements, we cannot make any statements on the muscle activation strategies that were used by participants. Furthermore, we did not assess (changes) in relative timing of inter-joint coupling. Studies have shown that a subgroup of patients with CLBP move their lumbar spine more readily through the available range than other joints (e.g. the hip joint). According to the kinesiopathologic model, this is a contributing factor to the development and persistence of LBP.[50,68] Therefore, it might have been valuable not only to have measured the amount of ROM, but also the timing of the inter-joint coupling. Finally, the lumbar spine was regarded as one segment, since lumbar kinematics were measured using sensors at the L1 and S1 level. It has been shown that regional differences between the movements of the upper and lower lumbar spine exist.[69-71] In most cases, LBP arises from the lower segments of the lumbar spine. Therefore, it might have been worthwhile to have assessed the improvements in ROM of these two lumbar regions separately. If the improvements were mainly due to a reduction of ROM in the upper lumbar spine, this might be regarded as a less favourable outcome. However, 8 out of 9 responders in the sensor group had a total lumbar ROM of less than 5° during the waiter's bow after the intervention. This strongly suggests that improvements in movement control were also obtained in the lower lumbar spine.

Part of the abovementioned limitations were due to the technical limitations of the ValedoMotion as a measurement tool. First, the ValedoMotion only contains three sensors, which restricted the number of regions that could be evaluated. Given the tasks that were assessed, we decided that it was also essential to measure the ROM in the hip joint. Therefore, we were unable to measure the movements in the upper and lower lumbar spine separately. Second, the ValedoMotion cannot be synchronised with external equipment, which prevented us from measuring muscle activity.

Notwithstanding the abovementioned methodological considerations, our study was innovative as it was the first to show that sensor-based feedback was more effective than conventional feedback to improve lumbopelvic movement control in patients with CLBP in the short term.

2.6 Virtual reality distraction

2.6.1 Immersive vs nonimmersive virtual reality

Immersion refers to the objective and quantifiable characteristics of the technological system,[5,72] such as the occlusion from the outside world, the presence of head-tracking or a high definition panoramic view. Therefore, virtual reality (VR) ranges from being fully immersive to nonimmersive.[73,74] Immersive VR environments are designed to give the user the illusion of going into a computer-generated virtual world, which is mostly achieved by using head mounted displays.[5,75] In a nonimmersive VR system, the user typically interacts with an environment that is displayed on a computer or TV-screen.[76,77] Thus, the interactive games that were used in our study can best be described as nonimmersive VR games.

Early studies in healthy volunteers conducted by the research group of Hoffman and colleagues demonstrated that immersive VR systems led to a greater analgesic effect than nonimmersive systems.[5,6,78] An essential difference between the two systems was that participants were able to interact with the immersive system, while this was not the case for the nonimmersive system. Indeed, subsequent studies in healthy volunteers have shown that the interactive aspect is important to explain the analgesic effect of VR games.[79-81] For example, a trial in healthy participants showed that the analgesic effect of interactive gaming was similar when games were played using a head mounted display (high immersion) compared to when the games were projected on a wall (low immersion).[80] However, the distraction via the head mounted display was superior to a non-interactive distraction (i.e. recalling pleasant experiences). The importance of the interactive element, rather than the full immersion into a VR environment, may explain why the nonimmersive VR distraction in our study resulted in a significant reduction in pain.

2.6.2 Virtual reality distraction in chronic pain

Previous to our study, the analgesic effects of VR distraction in patients with chronic pain had only been investigated during small and uncontrolled trials.[75-77,82-86] Typically, these studies have reported highly variable improvements in pain. For example, Cole et al. showed a clinically relevant reduction in pain (>30%)[87] in 8 out of 14 (57%) patients with chronic phantom limb pain when they played a VR game with their stump.[76] The effects of VR distraction were highly variable, as improvements ranged between 0-100%.[76] Similar numbers have been reported in other case series.[75,85] Overall, the results of these small studies are confirmed in our RCT. Thirty-three out of 42 (79%) patients experienced less pain during the VR games, while 22 out of 42 patients (52%) reported a decrease in pain larger than 30%. From this perspective, it may seem as if the VR distraction was not clinically effective for about half of the patients. However, instead of looking at within group differences, it is more important to consider the differences between groups. Indeed, the participants in the control group of our study reported an overall *increase* in pain during the exercises (Mean= 14.4%, SD= 33.5%, p= 0.02). As such, the difference between the VR and control group (Mean= 52.7%, SE= 8.5%) was actually larger than the within group difference of the VR group (Mean= 38.2%, SD= 43.7%).

Given the lack of controlled trials using VR distraction in patients with chronic pain, we can only compare our between group results to studies using a non-VR distraction. In this respect, Van Ryckeghem et al. recently published a meta-analysis that investigated the analgesic effects of distraction in chronic pain populations.[88] Of importance, no studies using VR distraction were included. They showed that distraction interventions did not significantly reduce the pain intensity when compared to a control condition receiving no specific instructions (Hedges' *g*= 0.10, p= 0.10). Although studies with a variety of chronic pain populations were included in this meta-analysis, none of the included trials that were conducted in a CLBP population (n= 4) showed that distraction was superior to a control condition.[88] In contrast, large effect sizes were found in our trial (Cohen's *d* range= 0.85 to 1.31). This may suggest that the differences between the results of this meta-analysis and our study are due to the type of distraction (VR vs non-VR), rather than the differences in patient populations. This is plausible, since VR distraction has already been shown to have a larger analgesic effect than non-VR distraction in patients with burn wounds undergoing wound dressing.[89] However, to confirm this in a chronic pain population, an RCT comparing a VR with a non-VR distraction intervention is needed.

2.6.3 Methodological considerations

According to the contemporary motivational perspective on the attention to pain,[90,91] the engaging and motivating character of VR games is an important aspect to explain the analgesic effects of VR distraction.[88,90] In this respect, the use of a single intervention session can be seen as a limitation of our study, because the motivation to play VR games may decrease over time.[92] Referring to our feasibility study, participants remained motivated to exercise throughout an 18-week intervention, but they also indicated that towards the end of the intervention, they mainly used the postural feedback instead of the VR games. Therefore, it would be valuable to investigate whether the analgesic effects of VR distraction are maintained over multiple sessions, and whether potential changes in motivation would influence these effects.

It has been hypothesised that the analgesic effect is not only dependent on the type of distraction (i.e. VR vs non-VR), but also on the pain-related cognitions and emotions of the individual.[88,91] Therefore, we investigated the moderating effects of pain-related fear and pain catastrophising on the VR induced analgesia. These factors were chosen since they are highly prevalent among patients with CLBP,[93,94] and because they can increase the attention to pain and the difficulty to disengage from it.[95-97] However, contrary to the abovementioned hypothesis, pain-related fear and pain catastrophising did not moderate the effects of VR distraction in our study. It could be argued that we should have measured the attention to pain in a more direct way, via the Pain Vigilance and Awareness Questionnaire,[98] or via experimental methods.[99-101] Van Ryckeghem et al. measured the attentional bias to pain-related information in an experimental way, and showed that this attentional bias moderated the effects of a non-interactive distraction task.[101] However, it should be noted that this study was conducted in healthy psychology students using experimentally induced pain, so we cannot simply extrapolate these results to the clinical pain in a chronic pain population.[101] In addition, there is debate about which paradigms should be used for assessing the attentional bias to pain, as different methods have been shown to yield different results.[99]

Another aspect that needs consideration is the type of exercises that was used in our study. The decision to use pelvic tilts in the sagittal plane was made for three reasons. First, the VR games were designed to be controlled with these movements. Second, pelvic tilt exercises in the sagittal plane were best suited to standardise the intervention. This was essential, because we tried to mimic the movements of participants in the VR group as closely as possible in the control group. Third, pelvic tilts in the sagittal plane are relevant, as they are often used in the rehabilitation of patients with CLBP.[1,102] Notwithstanding the valid reasons for choosing pelvic tilt exercises, it is possible that another type of exercise would have yielded different results. For example, if participants had to perform movements they were highly fearful of, such as lifting tasks,[54] it is possible that the VR distraction would have been less effective, or that the analgesic effects would have been moderated by pain-related fear or pain catastrophising. It has been shown that he extent to which pain captures attention is dependent on its threat value.[103] From the motivational perspective on the attention to pain,[90,91] patients are more likely to pursue a pain-related goal when the pain is perceived as a sign of bodily harm.[90] Under these circumstances, the processing of pain-related information will be enhanced, while the attention for information not related to the pain (i.e. the VR games) will be inhibited.[90] Therefore, it is possible that the effectiveness of VR distraction might be influenced by the type of task or exercise that is used.

3 Clinical implications

The overall aim of this PhD project was to investigate whether important aspects of, or barriers to exercise therapy could be addressed by using technology. This choice was based on the fact that little was known about the mechanisms via which technology could work. A better understanding of these mechanisms is crucial if we want to develop effective technology-supported exercise programmes. In this respect, our work provides essential insights that can be used to obtain this goal. However, given this more 'fundamental' approach, we should be prudent when making recommendations for clinical practice. These recommendations can be summarised as follows:

1. Sensor-based postural feedback could be used to support movement control exercises. In the short term, this type of feedback was more effective than conventional feedback to improve cognitive lumbopelvic movement control. In addition, we showed that it is feasible to provide this type of postural feedback at home.
2. Using VR games could be considered when it is deemed important to reduce the pain during or shortly after the exercises, even for patients with higher levels of pain-related fear, pain catastrophising and possibly for patients with more intense pain.

3. Technological support should be used within a clinical reasoning framework. As we have shown in this PhD project, some important underlying mechanisms can be addressed, but the results from our (updated) systematic review indicated that technology-supported exercises are not superior to conventional exercises. However, this may be due to a narrow approach to exercise therapy and a lack of clinical reasoning behind the use of technology. Below, I will discuss a few important aspects that need to be considered when deciding to use technological support during exercise therapy for patients with CLBP.

Choice of exercises: The choice of exercises should primarily be based on the clinical presentation of the patient, not on the possibilities or features of the technology. In other words, technology can be used if it can be integrated into the exercises that are appropriate for the patient, and if it can support important aspects of the exercises. Most of the commercially available technological systems that have been investigated in clinical trials were initially not developed for rehabilitation purposes.[21,23,104] As such, the applications of these technologies are often limited with regards to specific exercises for patients with CLBP. Moreover, as I have shown earlier, simply providing patients with standard active video games is not sufficient to improve pain and disability (also see paragraph 2.3.1).[9,13,28] Therefore, we should exploit the new possibilities created by technological systems, but it is crucial that our treatment complies with an evidence based approach and that technology is used within a clinical reasoning framework.

Patient preferences: When designing an exercise programme, it has been recommended to take the preferences of the patient into account.[105,106] In this respect, one of the aspects that should be considered is the treatment credibility and expectancy for recovery, as both factors have been shown to be associated with the outcome after a rehabilitation programme for patients with CLBP.[107,108] In general, most patients find technology-supported exercise therapy credible and they expect it to be helpful,[109] which was also shown in our feasibility study. However, individual differences exist about what is expected from the technology.[109] For example, our feasibility study showed that some patients prefer to receive exercises they can do during the day (e.g. at work) without having to use extra equipment. As such, when these patients would be dependent on technology to perform their exercises, this could actually be a barrier to do them. Therefore, it should be discussed with the patients whether they are willing to use technology.

Cost-effectiveness: Up till now, no cost-effectiveness studies exist that have compared two exercise programmes where the technological support was the single difference between the interventions. There is only one study that assessed cost-effectiveness, which showed that adding technology-supported movement control exercises to a standard treatment was more cost-effective than a standard treatment alone.[3,22] However, some aspects of this study need further consideration. First, the same results may also have been obtained by offering additional exercises without the technological support. Second, the extra cost per session due to the technological support was estimated to be 80 AUD (~50 €). Because participants were provided with technological support at home, one system could be used by about 12 patients per year.[22] In our feasibility study and the pilot trial by Hügli et al.,[24] the technological support at home was provided for about two months. Currently, the latest version of Valedo (ValedoPro) is on the market for 4500€.[110] A home version that works via a mobile app is also available for about 300€,[110] but this cheaper version does not have all the features of the Pro version, limiting its clinical utility. Given that physical therapists see hundreds of individual patients per year, it should be clear that the financial cost of buying multiple systems poses an important barrier for using this type of technology in clinical practice. Furthermore, in Belgium no patient reimbursement is available for these type of technological systems. At this moment (2019), a patient has to contribute 5.89 € per physical therapy session.[111] As such, it can be questioned whether patients are willing to buy a system of their own, even if it is a cheaper version. Finally, the time needed to set-up or explain the system to the patients should be taken into account. From our feasibility study, it became clear that it took about 20-30 minutes to explain patients how to use the Valedo. Zadro et al. reported that setting up and explaining a Nintendo Wii home exercise programme to persons >55 years old took about 1-2 hours, depending on the patients' understanding.[9] Given that patients typically receive 8-10 sessions of 30 minutes of individual physical therapy for LBP,[112] it is essential to take this time aspect into account.

4 Future directions

Every answer leads to more questions. Clearly, this PhD project is no exception to this rule. First, I will discuss the future directions for research based on the studies in this PhD project. Some aspects have already been covered in our limitations section of the general discussion, so they will not be repeated in full length here. Second, I will briefly look at technology-supported rehabilitation from a broader perspective.

4.1 Based on own research

4.1.1 Feasibility study

To assess the additional benefit of the technological support, an adequately powered RCT is necessary, in which the technological support is the single difference between the interventions. Because participants received 36 treatment sessions in our feasibility study, this number should be reduced in subsequent research to increase the external validity of the results. Further, it would also be of interest to collect the primary outcomes (e.g. pain and disability) at multiple time points, in order to assess the change over time. Efforts should also be made to assess the adherence to home exercises in a reliable way. A potential avenue is to use data that are stored on the system itself. This may be preferred, because there is evidence that self-reported measures of adherence are higher than those collected objectively by the technology itself.[113] Finally, an economical evaluation of the technological support is warranted.

4.1.2 Sensor-based postural feedback and movement control

Some of the potential aims of future research on sensor-based postural feedback have already been discussed. These can be summarised as follows:

- To compare sensor-based postural feedback to a therapist-led intervention.

- To assess what is the most effective way of providing sensor-based postural feedback. For example, visual feedback can be compared to auditory or vibrotactile feedback. Furthermore, different ways of presenting the visual feedback can be explored.
- To investigate whether the short term improvements are maintained in the long term.
- To assess other aspects of movement control, such as muscle activity patterns.

In addition to these aspects, it could be examined whether sensor-based postural feedback can also be provided during more complex movements. In our trial, participants practised a waiter’s bow. This could be considered as a relatively simple exercise in terms of movement characteristics, as the movements were performed in a single plane and at a self-selected pace. In contrast, most activities in daily life or during sports are performed faster and in combined movement directions (i.e. three-dimensional). As such, the stickman figure we used in our trial would not be suitable for providing feedback during three-dimensional movements. Other visual representations, such as the target game we used in our feasibility study could be used.

4.1.3 Virtual reality distraction

I have already covered a few important aspects that deserve attention in future research. These aspect can be summarised in the following research questions:

- Is a VR distraction more effective than a non-VR distraction in patients with chronic pain?
- Does the level of immersion influence the analgesic effect in patients with chronic pain?
- Does VR induced analgesia persist over multiple treatment sessions?
- Do more direct measures of attentional bias to pain moderate the analgesic effect of VR distraction?
- Does VR distraction have an analgesic effect during movements that are perceived as harmful?

Besides these research questions, the *mechanisms behind (VR) distraction induced analgesia* should be further investigated. It has been well established that a dysfunction of the endogeneous pain modulation system plays an important role in chronic pain.[114-116] However, while altered central pain processing has consistently been found in patients with fibromyalgia[117,118] and chronic whiplash associated disorders,[119,120] the picture in patients with CLBP is less clear,[117,121,122] which is probably due to the heterogeneity in this population (also see general introduction).[117] Since various studies have shown that descending inhibitory brain circuits are activated during the distraction from pain,[123,124] individual differences in pain processing may explain why VR distraction is more effective for some patients with CLBP compared to others. However, the relation between (alterations) in central pain processing and distraction induced analgesia is not straightforward, as two recent trials have shown that patients with fibromyalgia had normal (non-VR) distraction related pain inhibition compared to healthy persons.[125,126] Although the diagnosis of fibromyalgia is highly suggestive for the presence of altered central pain processing,[117,118] the latter was not explicitly tested in these studies (e.g. via conditioned pain modulation[118,127]). Therefore, a further exploration of the association between central pain processing and distraction induced analgesia is warranted. Related to this, the role of positive emotions that are experienced while playing VR games deserves further attention, as it has been shown that a positive emotional state decreases pain perception.[123,128] In addition, the attentional and emotional modulation of pain occurs in partially discernable brain circuits.[123,128,129] Potentially, the experience of positive emotions may explain why interactive VR games seem to be a more effective for reducing pain than (passive) non-VR distraction techniques, such as reading a list of neutral words.[130]

4.2 Taking on a broader view

Although it is beyond the scope of this dissertation to explore all potential applications of technology in the rehabilitation of patients with CLBP, some aspects are worthwhile pointing out.

Virtual reality may be useful to support exposure therapy for patients with CLBP and pain-related fear. In short, exposure therapy aims to change the erroneous beliefs of patients with CLBP that certain movements or activities are harmful for their spine, thereby creating an extinction of the pain-related fear and the avoidant behaviour.[131] One of the obstacles in clinical practice is obtaining the generalization of this extinction.[131] In part, this is due because pain-related fear is dependent on the context,[132] and it is difficult to recreate a multitude of different contexts in clinical practice. Potentially, by using VR, different realistic environments can be created so that patients can be exposed to their feared activities in various contexts, which may help to overcome this problem. Thomas & France suggest that VR games might also be useful in exposure therapy for patients with CLBP, because they can distract patients from their pain and motivate them to engage with their treatment.[133,134] Although this can be important given the high drop-out rates of exposure therapy,[131,135] VR distraction might also carry some risks, as distraction is a form of safety-seeking behaviour.[136] Although participants are not actively distracting themselves, they may still attribute the violation of their erroneous expectancies to the fact that they are only playing a game. Therefore, it can be questioned whether the treatment effects during games will be generalised to real world situations. Indeed, Thomas & France showed that patients with CLBP increased their lumbar flexion while playing a custom made VR game designed to obtain this goal, but this change in (avoidant) movement behaviour was not transferred to a real world lifting task (i.e. without VR).[133]

As I have previously shown, the costs of specific technological systems may be a barrier for their implementation into clinical practice. Therefore, it may be worthwhile exploring the use of readily available technologies, such as smartphones and the internet. Several reviews have been published that investigated mobile apps,[137,138] web based[139] or digital support[140] interventions for the self-management of LBP. Overall, these reviews show that web based and digital support interventions are not more effective than a waiting list or usual care, and that no cost-effectiveness analyses of these interventions have been performed.[138-140] In addition, Machado et al. reported that none of the mobile apps they reviewed had been evaluated in a clinical trial.[137] Further, a clear theoretical underpinning of the digitally delivered interventions was mostly lacking,[140] and many of the mobile apps offered poor quality information that was not in line with current recommendations.[137] These results suggest that digitally delivered self-management programmes are not (yet) a surrogate for face-to-face or therapist-led interventions. This is supported by a recent study by Geraghty et al., which compared usual care plus an internet intervention to support self-management, to the same treatment enhanced by support from a physical therapist.[141] Significantly more patients receiving the internet plus physical therapist support obtained a clinically relevant improvement in disability, compared to those with only support via the internet (59% vs 31% respectively).[141] Furthermore, the results from the systematic reviews reveal that digitally delivered interventions should be carefully developed by a consortium of specialists from different fields, including clinical experts, software developers, engineers and digital media experts. In addition, patients and therapists working in the field should be involved. The potential of using such an approach is shown in a recent study by Shebib et al.[142] They developed a digital care programme, including sensor-guided exercises, education, cognitive behavioural therapy and personal support from a therapist (via the mobile app or telephone). The intervention group who received the digital programme was compared to a control group that was told to be on a waiting list for this intervention, but who still had access to usual care. After a 12-week treatment period, the minimally clinical important difference in pain and disability was obtained by respectively 81% and 58% of the participants in the intervention group. In the control group, these numbers were 31% for pain and 25% for disability, which was significantly lower than in the intervention group.[142] It should be noted that the development of this programme involved different stakeholders (experts, patients and industry) and took two years of testing before the trial was started. Although, this study reveals the potential of technological support to improve the treatment for patients with CLBP, it also shows that developing evidence-based digital interventions is a long process, during which multiple stakeholders should be involved. Finally, cost-effectiveness studies are warranted and a legal framework (e.g. privacy, reimbursement) is necessary before these intervention can be implemented in daily clinical practice.

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Summary

Low back pain (LBP) is the leading cause of years lived with disability worldwide. Approximately 80% of people will experience at least one episode of LBP in their lifetime. Although an initial episode of acute LBP usually resolves within four to six weeks, pain flare ups are common and a significant amount of people develop chronic low back pain (CLBP, i.e. LBP that persists > three months). Moreover, about 15 to 25% of people are not fully recovered after one year. Besides the negative consequences of LBP on an individual level, it also poses an enormous economic burden on society, as it is the single most important reason for sick leave and early retirement. Therefore, optimizing the treatment for CLBP is paramount.

One of the most frequently used interventions for managing CLBP is exercise therapy. This type of treatment has consistently been shown to be effective in reducing pain and disability in patients with CLBP. However, the effect sizes are often small and not all patients respond well to exercise therapy. One of the main reasons that has been suggested for these modest results is the fact that in many clinical trials the interventions are not tailored to the individual patient. Indeed, given the heterogeneity within the CLBP population, a one-size-fits-all approach is unlikely to yield satisfactory treatment results. As such, we should aim to individualize the exercise programme based on the clinical presentation and treatment goals of the patient. Another aspect that needs to be considered are the numerous barriers to participate in a long term exercise programme, such as the lack of motivation, the experience of pain during exercises, not being supported during home exercises or a lack of time to exercise.

Given the small to moderate effects of ‘conventional’ exercise therapy for patients with CLBP, new approaches are warranted to improve treatment results. A potential avenue to obtain this is by using technological systems to support exercises, as technology may have the potential to remove barriers or to support aspects deemed important for treatment success after exercise therapy. Therefore, **we focused on three main aspects in this PhD project**: (1) the integration of technological support into an individually tailored exercise programme with home exercises, (2) the provision of external postural feedback to improve movement control and (3) using virtual reality (VR) distraction during exercises to obtain an analgesic effect.

Chapter I consists of a systematic review and a feasibility study. In our **systematic review (Study 1)**, we summarized the current evidence on the effectiveness of technology-supported exercise therapy (TSET) for patients with LBP. We showed that TSET is not more effective than other interventions or a placebo/waiting list to improve pain, disability or quality of life, even when only more recent trials were considered. In addition, when the technological support was the single difference between interventions, no between-groups differences could be found. A standard therapy combined with a TSET-programme led to larger improvements in pain and disability compared to a standard therapy alone. However, when TSET was added to a standard therapy that was already effective, the additional benefits of TSET were less clear. The lack of benefit from technological support may possibly be explained by the fact that technological support was not integrated into a programme containing individually tailored, functional and home exercises. To assess whether it is possible to implement technology (i.e. serious games and sensor-based postural feedback) into such an exercise programme, we conducted a **Feasibility Study** (Study 2). Ten patients with chronic non-specific low back pain (CNSLBP) and an underlying movement control impairment were recruited. All participants received an exercise programme that was based on the same principles of movement control training, but which was tailored to the individual patient. The technology-supported exercises were integrated into functional activities and technological support was provided at the rehabilitation centre and at home. Our study showed that is feasible to support a functional exercise programme with technology for patients with CNSLBP, both in a supervised and a home environment. Participants found the intervention credible and remained motivated throughout the study. In addition, no serious adverse events were reported. However, the time needed to set up the games was a barrier for home use and participants would have found it useful to have receive postural feedback during daily life activities. In addition, we were not able to measure the adherence to home exercises, which was an important limitation of this study.

In **Chapter II**, we explored whether movement control could be improved by sensor-based postural feedback. First, we conducted a **Reliability Study** (Study 3) in healthy participants to investigate during which movement movement control tasks we could assess lumbopelvic kinematics reliably and with sufficient agreement. We were mainly interested in establishing the minimal detectable change between two measurements (i.e. measurement error), as this would be essential for our intervention study (Study 4). Four different movement control tasks were assessed: waiter's bow (WB), stance-to-sit-to-stance (SIT), lifting a box from the floor (LIFT) and placing a box on an overhead shelf (OVERH). The maximal deviation from the starting position in the lumbar spine and hip were calculated for each task (i.e. range of motion expressed in degrees). Both the within and between session reliability of the WB and LIFT task were excellent (ICC range = 0.89 – 0.96), and the measurement error was acceptable (~5° in the lumbar spine, ~10° in the hip). Therefore, these two movement control tasks were used in our intervention study. In this **Intervention Study** (Study 4), we investigated whether **sensor-based postural feedback** was more effective than feedback from a mirror or no feedback to improve lumbopelvic movement control in patients with CNSLBP. In addition, we assessed whether patients with CNSLBP were equally capable of improving lumbopelvic movement control compared to healthy persons. During the intervention, participants practised the WB during 3 sets of 6 repetitions while receiving their designated form of feedback (i.e. from sensors, a mirror or no feedback). Our results showed that sensor-based feedback was significantly more effective than feedback from a mirror and no feedback to improve lumbopelvic movement control performance (measured with the WB) and motor learning (measured with the LIFT task). The between groups differences were also larger than the measurement error, except for the hip joint during the LIFT task. Patients with CLBP were equally capable of improving lumbopelvic movement control compared to healthy persons.

Finally, **Chapter III** consists of an **intervention study** in a CLBP population (Study 5) in which we assessed whether **virtual reality (VR) distraction** had an analgesic effect during and after exercises, and whether it influenced the time spent thinking of pain during the exercises. Furthermore, we investigated whether levels of baseline pain intensity, pain catastrophizing and pain-related fear moderated the effects of VR distraction. Participants in the intervention group played 2 VR games which had to be controlled using pelvic tilts. Participants in the control group tilted their pelvis according to an auditory signal. Our results showed that participants in the VR group experienced significantly less pain during and immediately after the exercises, and they spent significantly less time thinking of their pain compared to the control group. The effect sizes (Cohen’s *d*) were large, an ranged between 0.85 and 1.31. Baseline levels of pain intensity, pain-catastrophizing and pain-related fear did not moderate the effectiveness of the VR distraction.

In conclusion, this PhD project shows that technological support is able to remove barriers to, or to support important aspects of exercise therapy for patients with CLBP. In addition, we also demonstrated that it was feasible to integrate technological support into a tailored and functional exercise programme including home exercises. Furthermore, specific recommendations for future research were made. The results of the current PhD project can be used to develop effective technology-supported exercise programmes, based on sound clinical reasoning.

Samenvatting

Lage rugpijn (LRP) is wereldwijd gezien de belangrijkste oorzaak waarom mensen beperkingen ervaren tijdens hun dagelijkse activiteiten. Ongeveer 80% van de populatie zal ten minste een episode van LRP doormaken tijdens hun leven. Alhoewel een acute episode van LRP meestal opgelost is na vier tot zes weken, treedt er vaak herval op. Bovendien is er een deel van de patiënten dat evolueert naar chronische lage rugpijn (CLRP), wat wil zeggen dat klachten na drie maanden nog steeds aanwezig zijn. Zo zal 15 tot 25% van deze mensen na een jaar niet volledig genezen zijn van hun rugpijn. Naast de negatieve gevolgen op persoonlijk vlak, heeft LRP ook een enorme economische impact op de samenleving. Inderdaad, LRP is de belangrijkste reden van werkverzuim en het is de meest gerapporteerde oorzaak waarom mensen vroegtijdig op pensioen moeten gaan. Om deze redenen is het essentieel dat we verder onderzoek doen om de behandeling van CLRP te optimaliseren.

Een van de meest frequent gebruikte behandelingen voor CLRP is oefentherapie. Er is sterk bewijs dat oefentherapie de pijn en de beperkingen van patiënten met CLRP vermindert. Echter, deze positieve effecten zijn slechts van een kleine tot matige grootorde, en voor een deel van de patiënten lijken oefeningen niet veel beterschap te brengen. Een van de belangrijkste redenen voor deze matige resultaten is waarschijnlijk dat de oefenprogramma's niet op maat worden gemaakt van de individuele patiënt. Gezien de heterogeniteit binnen de populatie van patiënten met CLRP hoeft het niet te verwonderen dat een one-size-fits-all benadering niet tot bevredigende resultaten leidt. Daarom is het essentieel dat oefenprogramma's gebaseerd worden op het klinische beeld van de patiënt en dat er rekening gehouden wordt met de behandeldoelstellingen van het individu. Daarnaast zijn er een aantal factoren die belemmeren dat patiënten geëngageerd blijven om een langdurig oefenprogramma te volgen, wat een negatieve impact kan hebben op het behandelresultaat. Voorbeelden hiervan zijn een gebrek aan motivatie, het ervaren van pijn tijdens het oefenen, geen ondersteuning krijgen tijdens thuisoefeningen of een gebrek aan tijd om te oefenen.

Gezien de matige effecten van 'conventionele' oefentherapie voor mensen met CLRP is het nodig om nieuwe benaderingen te exploreren om alzo de behandelresultaten te verbeteren. Een potentiële manier om dit te bekomen is het ondersteunen van oefentherapie via het gebruik van technologische systemen. Deze systemen hebben de mogelijkheid om belangrijke aspecten van oefentherapie te ondersteunen, of om barrières voor het uitvoeren van oefeningen weg te nemen. **In dit doctoraatsproject, hebben we ons daarom gefocust op de volgende drie hoofdzaken**: (1) de integratie van technologische systemen in een geïndividualiseerd oefenprogramma met thuisoefeningen, (2) het geven van externe posturale feedback ter verbetering van de bewegingscontrole, en (3) het gebruik van virtual reality afleiding om zo een analgetisch effect te verkrijgen tijdens het oefenen.

Hoofdstuk I bestaat uit een systematische review en een haalbaarheidsstudie. In onze **systematische review** (Studie 1) hebben we de huidige evidentie omtrent technologie-ondersteunde oefentherapie (TOOT) voor personen met LRP samengevat. Hieruit bleek dat TOOT niet effectiever was dan andere interventies of een placebo interventie om de pijn, beperkingen en kwaliteit van leven te verbeteren. Indien we enkel de studies vergeleken waarbij de technologische ondersteuning het enige verschil was tussen de interventies, bleek dat er geen verschillen waren tussen beide groepen. Wanneer een standaard behandeling aangevuld werd met een TOOT-interventie, zagen we wel dat dit tot grotere verbeteringen in pijn en beperkingen leidde dan een standaard behandeling alleen. Er moet wel opgemerkt worden dat wanneer de standaard behandeling op zichzelf reeds effectief was, het bijkomende effect van de TOOT minder duidelijk werd. Het feit dat technologische ondersteuning geen additioneel voordeel biedt om de pijn, beperkingen of kwaliteit van leven te verbeteren kan mogelijks verklaard worden doordat in deze studies de ondersteuning niet geïntegreerd werd in een individueel aangepast oefenprogramma met thuisoefeningen. Om na te gaan of het mogelijk is om technologie in zo een oefenprogramma te implementeren, hebben we een **haalbaarheidsstudie** (Studie 2) uitgevoerd. Tien patiënten met CLRP en een onderliggende probleem met de bewegingscontrole van de lage rug werden geïncludeerd. Alle deelnemers aan de studie kregen een oefenprogramma dat was gebaseerd op dezelfde principes, maar dat wel was aangepast aan de individuele patiënt. De technologie-ondersteunde oefeningen werden geïntegreerd in functionele activiteiten en de technologische ondersteuning was tevens beschikbaar in de thuissituatie. De resultaten van onze studie toonden aan dat het haalbaar was om dergelijk oefenprogramma aan te bieden aan patiënten met CLRP. De deelnemers vonden de therapie geloofwaardig en doorheen de studie bleven ze gemotiveerd om de oefeningen te doen. Verder werden er geen serieuze negatieve effecten gerapporteerd. De tijd die nodig was om het technologische systeem op te starten was duidelijk een barrière om het te gebruiken in de thuissituatie, en de meeste patiënten zouden het ook nuttig gevonden hebben indien ze de posturale feedback ook tijdens dagelijkse bezigheden hadden kunnen krijgen. Een belangrijke limitatie van deze studie was dat we niet in staat waren om de therapietrouw in verband met de thuisoefeningen te meten.

In **Hoofdstuk II** zijn we nagegaan of het mogelijk was om de lumbopelvische bewegingscontrole te verbeteren door middel van posturale feedback die gegeven werd via bewegingssensoren. Vooraleer deze studie aan te vatten, hebben we een **betrouwbaarheidsstudie** (Studie 3) uitgevoerd om na te gaan welke functionele bewegingscontroletaken op een betrouwbare en accurate manier gemeten konden worden. We waren voornamelijk geïnteresseerd om de meetfout vast te stellen, aangezien dit noodzakelijk was voor onze interventiestudie (studie 4). Er werden vier bewegingscontroletaken gemeten: Een heupbuiging met neutrale lage rug (WB), een stand-zit-stand taak (SIT), het opheffen van een bak op de grond (LIFT) en het bovenhoofds heffen van een klein bakje (OVERH). Voor elke taak werd de maximale deviatie van de startpositie gemeten in de lumbale wervelkolom en het heupgewricht, en dit werd uitgedrukt in het aantal graden. Zowel de betrouwbaarheid binnen een sessie als de betrouwbaarheid tussen twee sessies was excellent voor de WB en de LIFT (ICCs tussen 0.89 en 0.96). Tevens was de meetfout acceptabel (~5° voor de lumbale wervelkolom, ~10° voor het heupgewricht). Daarom werden deze twee taken gebruikt in onze interventiestudie. In deze **interventiestudie** (Studie 4) hebben we onderzocht of **sensor-gebaseerde posturale feedback** effectiever was dan feedback van een spiegel of geen feedback, om de lumbopelvische bewegingscontrole te verbeteren. Daarnaast zijn we nagegaan of patiënten met CLBP even goed in staat waren om hun bewegingscontrole te verbeteren in vergelijking met gezonden personen. Tijdens de interventie oefenden de deelnemers de WB gedurende drie sessies van zes herhalingen, terwijl ze hun toegewezen vorm van feedback kregen (van de sensoren, spiegel of geen feedback). Onze resultaten toonden aan dat sensor-gebaseerde feedback effectiever was dan feedback van een spiegel of geen feedback om de lumbopelvische controle tijdens de WB te verbeteren. Verder was dit type van feedback ook effectiever om het motorisch leren verbeteren (gemeten met LIFT). Uit onze resultaten bleek ook dat patiënten met CLRP even goed in staat waren om hun lumbopelvische controle te verbeteren in vergelijking met gezonde personen.

Hoofdstuk III bestaat uit een **interventiestudie** bij patiënten met CLRP, waarin we onderzocht hebben of **virtual reality (VR) distractie** een analgetisch effect had tijdens en na het oefenen. Tevens zijn we nagegaan of VR distractie de tijd die gespendeerd werd aan het denken aan pijn beïnvloedde. Als laatste hebben we onderzocht of de mate van pijnintensiteit, pijn-gerelateerde angst en catastroferende gedachten (gemeten voor het onderzoek) een invloed hadden op het effect van de VR distractie. De deelnemers in de interventiegroep speelde twee VR games die bestuurd moesten worden door bekkenkantelingen. De deelnemers in de controlegroep kantelden hun bekken op het ritme van een auditief signaal. Onze resultaten toonden aan dat in vergelijking met de controle groep, de personen in de interventiegroep significant minder pijn ervaarden tijdens en na het oefenen, en dat ze ook minder aan hun pijn dachten. De mate van pijnintensiteit, pijn-gerelateerde angst en catastroferende gedachten hadden geen invloed op de effectiviteit van de VR distractie.

De algemene conclusie van dit doctoraatsproject is dat we via technologie belangrijke aspecten van oefentherapie kunnen ondersteunen, en barrières voor het uitvoeren van oefeningen weg kunnen nemen. Tevens hebben we aangetoond dat het mogelijk is om technologische ondersteuning te integreren in een individueel aangepast oefenprogramma met thuisoefeningen. Bijkomend werden er aanbevelingen gedaan voor verder onderzoek. De resultaten van dit doctoraatsproject kunnen gebruikt worden om effectieve technologie-ondersteunde oefenprogramma's te ontwikkelen die passen binnen een evidence-based klinisch redeneermodel.

Professional Career

Biography

Thomas Matheve was born on the 7th of March 1981 in Geel, Belgium. In 2004, he obtained his Master's degree (Licentiaat) in Physiotherapy and Rehabilitation Sciences magna cum laude at KU Leuven, and specialised in musculoskeletal rehabilitation. Until 2013, he worked as a (part-time) self-employed physiotherapist at a private practice in Leuven. Thomas combined this work with a job as a teaching assistant at KU Leuven (2004-2005) and he has also worked at the University hospital of Leuven (2005-2006). In 2008, he became a part-time teaching assistant at the physiotherapy department at Provinciale Hogeschool Limburg, which later migrated to Hasselt University. In 2013, Thomas quit his job as a self-employed physiotherapist and started his part-time PhD (55%), which he is currently combining with his part-time job as a teaching assistant in musculoskeletal rehabilitation (45%). Thomas' PhD project is supervised by Prof. Annick Timmermans and since 2017, it is co-supervised by Prof. Simon Brumagne (KU Leuven). Besides his work at the university, Thomas is a board member of the Limburgs Congres voor Sportgeneeskunde since 2013.

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Finally, I have a few words for **Clair**, a.k.a. Dr Drap. It is 3 years to the day we first met. I'm glad you have a good taste in music (I'll forget your reggae stuff for a moment) and beer, so you digged De Blauwe Kater. Thanks for all your support through the years and just for being you. You even sacrificed your last Easter holidays by going to Vietnam, so I could focus on writing my thesis :). Can't wait for our next adventures to begin!