The Effect of Real-time Biofeedback on Lumbar Spine and Lower Limb Kinematics and Kinetics during Repetitive Lifting

Yanto Naudé

A thesis submitted to Auckland University of Technology in

fulfilment of the requirements for the degree of Master of Philosophy (MPhil)

2018

Faculty of Health and Environmental Sciences

Primary supervisor: Prof Mark G Boocock

Secondary supervisor: Dr Grant A Mawston

Table of Contents

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Candidate: Date: 14/03/2018

List of Figures **Page**

List of Tables

Page

Glossary of Abbreviations

2D	two dimensional
3D	three-dimensional
ACC	Accident Compensation Corporation.
BF	biofeedback group
CI	confidence interval
CLBP	chronic low back pain
CVA	cerebrovascular accident
EMG	electromyography
GUI	graphical user interface
H0	null hypothesis
H1	alternative hypothesis
HR	heart rate
HRV	heart rate variability
ICC	intra-class correlation coefficient
L1	first lumbar vertebra
L5	fifth lumbar vertebra
LBP	low back pain
LBI	low back injury
LS	lumbosacral
LSF	lumbosacral flexion
N	newton
NBF	non-biofeedback group
NSLBP	non-specific low back pain

OR	odds ratio
PSIS	posterior superior iliac spine
ROM	range of motion
RCT	randomized control trial
RPE	rating of perceived exertion
RR	relative risk
S1	first sacral vertebra
TF	trunk flexion
VR	virtual reality

Acknowledgements

I would like to thank Prof. Mark Boocock for his support and mentoring during the thesis process. From start to finish you were always a guiding hand and a knowledgeable voice to talk things over. Thank you for your invaluable input in the final write up stage of my thesis.

I would also like to thank Dr Grant Mawston for his support and encouragement throughout. Thank you for providing me with all your knowledge and experience in this area and for guiding me through the practical aspects, such as data collection, and for reviewing my work.

I would like to thank Nick Dominick and Ariane Williams for assisting in those long hours of data collection, often on the weekends or at night. Thank you also Nick for your tireless effort to process the volumes of data with me!

Thank you to Dr Jeff Kilby and his students, Madonna Bekhit and Joseph Vdv, for the software development of the sensors and for training 'us physios' how to use it. I would like to acknowledge Steve Taylor for his input in the development of the statistical models for this research. Thanks to Nico Magni for volunteering to be the photographic model for this thesis and subsequent publications.

A huge thank you to all the participants involved in this project who were of course an integral part of the overall process.

Thanks to my parents, Stefan and Cynthia, for their support and encouragement through the years which has enabled me to aspire to a higher education.

I would like to thank our children Caitlin, Thomas and Zac for always being supportive and enduring of 'Dad's thesis'.

I would like to give special thanks to my wife, Sarah, who has been my rock to lean on through difficult times and to celebrate the successes with throughout the process, for always providing me with encouragement and for all the sacrifices you had to make so that I could complete my thesis.

I would like to acknowledge Auckland University of Technology Ethics Committee for the ethics approval for this thesis (14/196) which was granted on the 9th of July 2014.

Abstract

The incidence of low back pain (LBP) in occupations that involve repetitive lifting is disproportionately high compared to other physical occupations. This has been attributed to prolonged and sustained end range spinal flexion over a working day, often due to impairments in postural awareness related to fatigue and creep. Physiotherapists will often provide advice on manual handling techniques to improve lifting posture, however, adherence is often brief and not easily transferable to the workplace. This has prompted health practitioners to find alternative workplace interventions approaches, such as real-time biofeedback.

A systematic review was initially conducted of randomised and non-randomised studies to determine the level of clinical evidence for real-time postural biofeedback as an approach to changing spinal posture. The review identified a low level of clinical evidence for the use of biofeedback as a treatment adjunct to effect changes in spinal posture, primarily due to the small number (8) of low quality studies. No studies considered the influence of biofeedback during highly repetitive manual handing tasks, where the ability to affect postural changes may be compromised due to fatigue.

An experimental study was conducted with the primary aim of assessing the effectiveness of real-time postural biofeedback on modifying lumbosacral (LS) posture during a repetitive lifting task. A secondary aim was to investigate the biomechanical changes (kinetic and kinematic) on the lumbar spine and lower limbs. Thirty-four participants were randomly allocated to 2 groups: a biofeedback (BF) / intervention group; and a non-biofeedback (NBF) / control group. Participants lifted a 13kg box at a frequency of 10 lifts per minute for up to 20 minutes. Two wireless inertial sensors attached to the lumbar spine provided real-time biofeedback on lumbar posture when lumbar flexion exceeded 80% maximum flexion. A nine-camera motion analysis system was used to record three dimensional (3D) motion, and in conjunction with 3D ground reaction forces, provided kinematic and kinetic data for input into a biomechanical model used to estimate joint reaction forces and joint moments. Bending moments on the passive structures of the lumbar spine were also calculated. Ratings of perceived exertion (RPE) were recorded throughout the lifting task.

Biofeedback resulted in significantly reduced peak lumbar flexion over the duration of the task, compared to the NBF condition. The BF group was able to maintain a LS sagittal plane

posture within the designated range (<80% maximum flexion), whereas, the group without feedback displayed a linear increase in trunk and LS flexion, reaching approximately 99% of maximal flexion at 20-minutes. Furthermore, the BF group adopted greater knee flexion, and increased hip and knee extension angular velocities compared to the NBF group. Whilst there were no differences between groups in the bending moment on the lumbar spine, estimates of biomechanical loads on the passive structures of the lumbar spine showed significant differences. Participants who received biofeedback did not become reliant on feedback, as demonstrated by reaching a peak after seven minutes of lifting followed by a progressive decline in the amount of feedback. Although the BF group might be considered to have adopted a physiologically more challenging lifting posture (i.e. semi-squat type posture), ratings of perceived exertion (RPE) suggested no difference between groups.

Providing biofeedback on lumbosacral flexion (LSF) during repetitive lifting appears beneficial in avoiding end range of LF and reducing the passive loading on the musculoskeletal structures of the lumbar spine. Thus, biofeedback of the LS posture offers a potential preventative and treatment adjunct to educate clients about their lifting posture. This could be particularly important for young, inexperienced workers employed in repetitive manual handling who appear at increased risk of back injury. When presented with biofeedback on lumbar posture, a strategy adopted by participants involved increased knee and hip angular velocities. Therefore, it may be prudent to consider lower limb power training, such as plyometrics, as part of an educational lifting programme.

Chapter 1: Introduction

Low back pain (LBP) is a major health issue throughout the world and is highly prevalent in today's society with more than 80% of individuals experiencing LBP at some point in their life (De Luca, 1997; Hoy et al., 2012; Vos et al., 2016). The global point prevalence of LBP has been estimated at 12% and the one month prevalence at 23% in a recent systematic review (Hoy et al., 2012). The reoccurrence of LBP is also high with a third of those experiencing LBP going on to have three or more episodes within 12 months (Hoy, Brooks, Blyth, & Buchbinder, 2010). Between July 2015 to June 2016, the Accident Compensation Corporation (ACC) of New Zealand reported 265,000 new cases and 340,000 ongoing back injury claims, affecting nearly one in every ten New Zealanders (Accident Compensation Corporation, 2016). Direct costs associated with LBP include medical treatment, medication and compensation, which are estimated to cost the New Zealand economy NZ$430 million annually (Accident Compensation Corporation, 2016). Globally, the picture is much the same, with annual costs of LBP in the United States estimated to be in excess of US$100 billion (Katz, 2006).

Manual handling is considered a leading cause of work-related LBP (da Costa & Vieira, 2010; Kuiper et al., 1999; NIOSH, 1997) and individuals engaged in activities, such as heavy and repeated lifting in flexed lumbar postures are at a particularly high risk of LBP (Arjmand, Shirazi-Adl, & Bazrgari, 2006; Kelsey et al., 1984; Magnusson et al., 1990; Marras et al., 1993). In a review of the epidemiology and aetiology of LBP, Cole and Grimshaw (2003) found 80% of all spinal injuries sustained from manual handling affected the lumbar spine.

Biomechanical risk factors related to LBP in occupations involving manual handling include; the magnitude of trunk flexion (TF), frequency of TF, time spent in a forward flexed trunk posture and maximal trunk angular velocity (Hides, Richardson, & Jull, 1998; Marras, Lavender, Ferguson, Splittstoesser, & Yang, 2010; Ramond-Roquin et al., 2015). This epidemiological evidence is supported by *in-vitro* biomechanical studies that have shown fatigue failure of the spine occurs more rapidly when the lumbar spine is flexed towards the end range of flexion (Gallagher et al., 2007; Solomonow, 2012; Solomonow, Zhou, Baratta, Lu, & Harris, 1999). Towards end range of flexion (80% or more), anterior shear forces and bending moments increase and greater loads are placed on the passive structures of the spine, increasing the risk of injury (Dolan & Adams, 1998; Dolan, Mannion, & Adams, 1994; Gallagher et al., 2007; Potvin, Norman, & McGill, 1991).

Physiotherapists and other healthcare professionals often prescribe lower back postural training, such as visual feedback, for manual handling as an approach to prevent, manage and rehabilitate LBP sufferers (McGill, 2007). Despite evidence of short-term changes to postural kinematics and kinetics (Mawston, McNair, & Boocock, 2007; Montgomery, Boocock, & Hing, 2011; K. O'Sullivan, O'Sullivan, Campbell, O'Sullivan, & Dankaerts, 2012), the ability to maintain this posture long-term is unclear, especially when individuals become fatigued (Boocock, Jackson, Burton, & Tillotson, 1994; Roy, De Luca, & Casavant, 1989). Fatigue-related changes in lifting posture could be attributed to the impairment of the body's intrinsic feedback system, or afferent information from muscles and ligaments to the sensory-motor cortex (Solomonow, Zhou, Harris, Lu, & Baratta, 1998; Solomonow et al., 1999), and/or reduced neuromuscular control of the spine (Granata & Gottipati, 2008; Mawston et al., 2007; Parnianpour, Nordin, Kahanovitz, & Frankel, 1988). Impairment of the intrinsic feedback system can lead to a reduced awareness of the lumbar postures and in turn cause abnormal loading across joint surfaces (Forwell & Carnahan, 1996) that may heighten injury and pain mechanisms (P. O'Sullivan et al., 2003).

Augmented feedback (Schmidt & Wrisberg, 2008) or external feedback may be an appropriate method to reduce unsafe spinal postures when intrinsic feedback is impaired (Herbert, Heiss, & Basso, 2008). The clinical evidence to support the use of external real-time feedback for effecting changes in spinal posture is based on a small number of limited quality studies (Breen, Nisar, & Ólaighin, 2009; Çelenay, Kaya, & Özüdogru, 2015; Dean & Dean, 2006; Lou, Lam, Hill, & Wong, 2012; Magnusson, Chow, Diamandopoulos, & Pope, 2008; Ribeiro, Sole, Abbott, & Milosavljevic, 2014; Vignais et al., 2013; Wong & Wong, 2008). There is a dearth of literature on the effectiveness of real-time biofeedback for affecting changes in spinal posture during the performance of manual handling tasks. Furthermore there is limited information on the effectiveness of biofeedback during a fatiguing task, or how individuals affect change in lifting technique in response to feedback and whether this can be sustained.

The aim of this study was to investigate the effects of real-time biofeedback on lumbar postural control and lifting strategy during a repetitive lifting task. It was hypothesised that restricting/limiting lumbar spine flexion below a prescribed threshold would become progressively more difficult due to the fatiguing effects of the repetitive lifting task, necessitating greater feedback. A secondary aim was to evaluate lower back and lower limb kinematics and kinetics in response to real-time biofeedback.

The outcome of this study will inform approaches to manual handling training and rehabilitation aimed at reducing the risk of LBP during repetitive lifting. It will provide objective evidence about LS posture and the use of external real-time biofeedback to influence postural kinematics and kinetics during repetitive manual handling tasks. The findings from this study are likely to be of significance for healthcare professionals, health and safety providers and those involved in manual handling training; providing knowledge that can be applied in the prevention, management and rehabilitation of workers employed in manual handling occupations.

Chapter 2: Narrative and Systematic Literature Review

2.1 Introduction

This chapter consists of two separate reviews; a narrative review and a more detailed systematic review. The narrative review will concentrate on: 1) an outline of the global prevalence and epidemiology of LBP; 2) the biomechanical risk factors associated with LBP, more specifically posture and fatigue; 3) a discussion of LBP interventions focussing on biofeedback approaches targeted at influencing behaviour. Finally, the systematic review of the literature will determine the current level of evidence for postural biofeedback as an approach to influence spinal kinematics.

2.2 Narrative Literature Review Search Process

A search of the literature was undertaken in September 2015 and repeated in July 2017. The electronic databases searched were Scopus; Medline; CINAHL Plus; Academic Search Premier; SPORTDiscus; Ergonomics Abstracts; PubMed; PEDro; and Cochrane. The search covered three main themes: 1) the prevalence and epidemiology of LBP; 2) posture and fatigue related biomechanical risk factors associated with LBP; and 3) behaviour change interventions which focus on biofeedback. The search method used different combinations of search terms which varied according to the databases used (Table 2.1). Details of the systematic literature review are described later in Section 2.8.

Pertinent articles were initially screened by title and, if deemed appropriate, the abstract was read. Additional literature was identified from a search of in-text citations of these articles. Only articles published in English up to July 2017 were included.

Table 2.1 Narrative literature search themes and terms

	Key search themes	
Epidemiology	**Biomechanical Risk Factors** (Postural and fatigue related)	**Biofeedback** (Interventions)
Low* back pain	Posture*	Biofeedback
Chronic low* back pain	Biomechanic*	Postural feedback
Low* back injur*	Risk factor*	Perceptual feedback
Lumbar	Repetitive	Feedback

Epidemiology	Lifting	Rehab*
Prevalence	Low* back pain	Intervention*
Aetiology	Low* back injur*	
	Lumbar	
	Fatigu*	

2.3 Epidemiology of LBP

2.3.1 Prevalence and Cost of LBP

LBP remains a common and costly problem. Between 60% - 80% of adults experience an episode of LBP at some point in their life (Dillingham, 1995; Waddell & Burton, 2001). Global estimates of LBP suggest a point prevalence rate of 11.9 ± 2.0% and a one month prevalence of 23.2 ± 2.9% (Hoy et al., 2012). Once affected, the recurrence of LBP is high, with between 24% and 80% of LBP sufferers going on to experience further episodes within twelve months (Hoy et al., 2010). In the period from July 2015 to June 2016, the Accident Compensation Corporation of New Zealand reported 265,000 new and 340,000 ongoing back injury claims, affecting nearly one in every ten New Zealanders (Accident Compensation Corporation, 2016). Between 10 to 40 percent of these disorders are considered chronic (Dillingham, 1995). Epidemiological evidence demonstrates that over half of LBP developed in the first year of employment and among the young, inexperienced workers (Van Nieuwenhuyse et al., 2004).

LBP is not only a common health disorder but it is costly and associated with prolonged absence from work (Ihlebaek et al., 2006). The annual cost of back injuries in New Zealand is estimated to be NZ$430 million (Accident Compensation Corporation, 2016), which is primarily associated with healthcare provision, e.g. physiotherapy, inpatient services, and pharmaceutical costs (Dagenais, Caro, & Haldeman, 2008). Globally, the picture is much the same. In the United States the estimated annual cost of LBP is between US$100 to US$170 billion (Katz, 2006; Manchikanti, Singh, Falco, Benyamin, & Hirsch, 2014). The indirect costs associated with LBP are more difficult to quantify, but commonly include costs related to employment and household productivity (Dagenais et al., 2008). Employment costs include absence from work, resulting in lost productivity or absenteeism and decreased productivity of those that continue to work (Goetzel, Hawkins, Ozminkowski, & Wang, 2003). In Great Britain, it was estimated that from 1994 to 1995 approximately 116 million work days were lost due to LBP (Maniadakis & Gray, 2000). Presently, this would equate to approximately £160 billion from work incapacity due to LBP. In addition to lost work productivity, individuals with LBP may also experience productivity losses at home if they are unable to complete routine household tasks, for example, cleaning, cooking, and home maintenance (Dagenais et al., 2008). These individuals often rely on outsiders to complete such tasks on their behalf, or on unpaid household members (Dagenais et al., 2008).

2.3.2 LBP Classification

One of the difficulties in identifying risk factors associated with LBP is the diagnosis and classification of LBP (Nachemson, 1992; Waddell, Somerville, Henderson, & Newton, 1992). Despite advances in radiological imaging, specific radiological diagnosis of LBP is unreliable (Borkan et al., 2002) and 85% of back pain cases fall under the umbrella of non-specific low back pain (NSLBP) (Dillingham, 1995). NSLBP conceals a number of conditions, some or all with different aetiologies (Leboeuf-Yde, Yashin, & Lauritzen, 1996). It has been suggested that there are different causal mechanisms at different stages in the development of LBP (Krause & Ragland, 1994), further complicating the identification of risk factors. For example, damage to the supraspinous ligaments could be caused by repetitive lifting at low velocities and loads, or alternatively the same ligaments could be damaged by a single high velocity and high load lift. Both causal mechanisms would lead to a similar injury, particularly in the acute stage. Figure 2.1 illustrates possible multiple causes of LBP and there often being more than one cause that leads to a certain type of LBP.

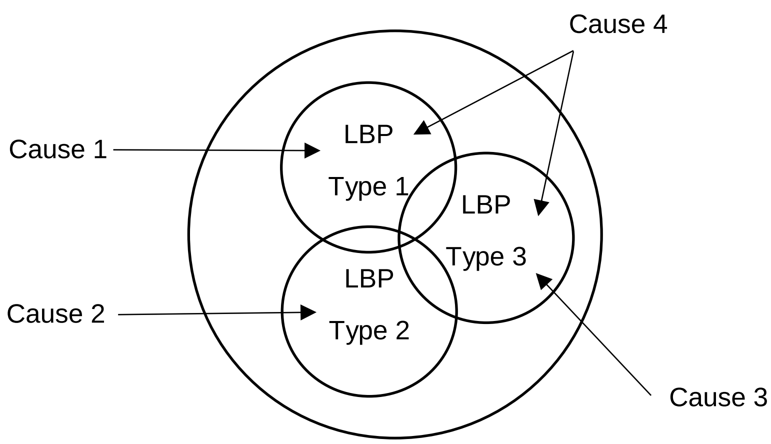

Figure 2.1. Schematic diagram of NSLBP and how it may consist of subtypes of LBP with different causal mechanisms (adapted from Leboeuf-Yde et al. (1996)).

2.3.3 The Aetiology of LBP

The aetiology of LBP is considered multifactorial (Linton et al., 2008; McGill, 2015; P. O'Sullivan, 2005) and can broadly be categorized into three domains: 1) psychosocial; 2) individual; and 3) biomechanical risk factors (Marras et al., 1995). Psychosocial factors include factors such as coworker support, job satisfaction and the perception of being more highly educated (Norman et al., 1998). Strong evidence has been found for low social support in the workplace and low job satisfaction as risk factors for back pain (Hoogendoorn, van Poppel, Bongers, Koes, & Bouter, 2000). Individual factors include age, isometric strength or endurance, work experience, aerobic capacity, height and weight (Bigos et al., 1986). Although psychosocial and individual risk factors are important to consider in relation to LBP (McGill, 2015), the current review will focus on biomechanical risk factors as they relate more specifically to postural movement as the aim of the study was to examine the effects of biofeedback on lumbar postural control and lifting strategy.

2.4 Biomechanical Risk Factors

Occupations involving repetitive heavy lifting in flexed lumbar postures are considered high risk of low back injury (LBI) (Arjmand et al., 2006; Kelsey et al., 1984; Magnusson et al., 1990; Marras et al., 1993). Ramond-Roquin et al. (2015) investigated the biomechanical risk factors associated with LBI and surveyed over 2160 workers across a variety of occupations and industries and found that the most powerful predictors of LBP were frequent forward bending (odds ratio (OR) = 1.45; 95% confidence interval (CI) = 1.07–1.97) and bending forward and sideways (OR = 2.13; 95% CI= 1.52–3.00). Similarly, Norman et al. (1998) performed a study at an-auto assembly plant with 10,000 hourly paid workers and found that peak lumbar flexion (OR = 2.4; 95% CI= 1.5–3.8), peak lumbar moment (OR = 1.9; 95% CI= 1.4–2.6), and peak lumbar shear force (OR = 2.3; 95% CI= 1.6–3.4) significantly increased the risk of LBP. When all these risk factors were found to be present, the risk of LBP was found to increase tenfold (Hides et al., 1998).

Repetitive lifting has been shown to generate a high bending moment on the passive structures (e.g. lumbodorsal fascia, supraspinous ligaments and other osteoligamentous structures) of the lumbar spine (Bonato et al., 2003). The high bending moments produced during lifting are considered to increase the risk of disk herniation and damage to the passive structure of the lumbar spine (Bonato et al., 2003). Beyond 80% LSF, the contribution to the extensor moment shifts from the back extensor muscles (active system) to the posterior passive structures of the spine (Dolan, Earley, & Adams, 1994; Howarth & Mastragostino, 2013). This can also result in increased anterior shear forces on the lumbar spine, increasing the risk of ligament injury and, if performed repetitively, can lead to vertebral end plate damage (Dolan, Earley, et al., 1994; Gallagher et al., 2007)

Lifting produces reactive forces acting in opposition to the object being lifted, for example, placing high compression forces on the spine (Bouisset & Zattara, 1987). The National Institute for Occupational Safety and Health (NIOSH) standards recommend that manual handling tasks generating spinal compressive forces in excess of 3400 N (Action Limit) should be redesigned to reduce the risks and those that result in 6400 N (maximum permissible limit) should be eliminated (Waters, Putz-Anderson, & Garg, 1994). Vertebral end plate damage values derived from cadaver lumbar intervertebral joints range between 4000 newton (N) to 12,000 N (Burgess-Limerick & Abernethy, 1997; Callaghan & McGill, 2001; Marras et al., 1995). The spine is particularly prone to the effects of such reactive forces due to its multi-segmental nature and dependence on muscles to actively provide spinal stability (Crisco & Panjabi, 1991; Panjabi, 2006).

2.5 Repetitive Lifting: Effects of Fatigue on Spinal and Lower Limb Kinematics and Kinetics

Fatigue, due to repetitive lifting, has been shown to change lifting technique with participants often increasing lumbar flexion and reducing knee flexion over time (Boocock, Mawston, & Taylor, 2015; Dolan & Adams, 1998; Sparto, Parnianpour, Reinsel, & Simon, 1997). For example, Sparto et al. (1997) conducted a repetitive lifting study among healthy adults and found the amount of lumbar flexion was greater at the end (4° increase) when compared to the beginning of the lifting task. They also found that knee and hip range of motion (ROM) was significantly less at the end of the lifting task. There was also reduced knee and hip angular velocities at the end of the task. The study concluded that this change in posture (greater lumbar flexion and reduced knee and hip ROM) represented a less physiologically demanding lifting technique due to the reduced recruitment of knee and hip musculature (Sparto et al., 1997).

Dolan and Adams (1998) also found increases in lumbar flexion during repetitive lifting study among healthy control subjects. They found a small reduction in bending moment and compressive forces throughout the lifting task. However, lumbar flexion increased significantly ($p = 0.008$) from 83% to 90% of maximal flexion, resulting in an estimated 36% increase in peak bending moment resisted by the passive tissues (posterior ligamentous system) of the lumbar spine. The increase in lumbar flexion was attributed to erector spinae muscle fatigue leading to compensatory recruitment of passive structures to resist the bending moment. Small increases in lumbar flexion close to the limit of movement (80-100% of maximal flexion) caused large increases in bending moment resisted by the passive structures of the lumbar spine (Dolan & Adams, 1998).

End range repetitive flexion has been shown to greatly increase the risk of spinal injury (Gallagher et al., 2007). Gallagher et al. (2007) showed that there was a 50 fold increase in the fatigue failure of spinal segments following repetitive loading responses at 45° of flexion compared to the reference position of 0°.

2.5.1 The Effects of Fatigue on Postural Awareness

Fatigue has been described as a physiological response that influences the intrinsic feedback system of the body that can lead to a significant reduction in sensation of body posture (proprioception) (Sparto, Parnianpour, Reinsel, & Simon, 1996; Taimela, Kankaanpää, & Luoto, 1999) and reduced neuromuscular control of the spine (Granata & Gottipati, 2008; Mawston et al., 2007; Parnianpour et al., 1988). Reduced proprioception is believed to play an important part in these motor impairments and symptoms (Panjabi, 2006; Ribeiro, Sole, Abbott, & Milosavljevic, 2011), and, more specifically, when individuals become fatigued, they have an altered sense of spinal position (Taimela et al., 1999). These changes can be seen experimentally as a decline in motor performance (Sparto et al., 1996) and an increase in spinal repositioning error (Mehta, Lavender, & Jagacinski, 2014). Research involving animals and humans suggest that afferent information from muscles and ligaments to the sensory-motor cortex is reduced during fatigue (Solomonow et al., 1998; Solomonow et al., 1999).

2.5.2 The Effects of Repetitive Flexion and Fatigue on the Passive Structures of the Spine

A reduction in afferent feedback to the central nervous system has been linked to alterations in motor unit recruitment and increased stretching of the viscoelastic structures of the spine (creep) (Sanchez, Adams, & Dolan, 2006). For example, in animal studies, repeated lumbar flexion leads to decreased paraspinal muscle activity in the first hour and a decrease in tissue resistance to loading (creep) (Solomonow, 2012; Solomonow, Zhou, Lu, & King, 2012). *In-vivo* human research has also found reduced passive stiffness and increased range of passive spine flexion, a further indication of creep, after 30 minutes of repetitive lifting (Parkinson, Beach, & Callaghan, 2004). When creep occurs in the spinal tissues, evidence suggests delayed activation of the back muscles (Sanchez et al., 2006). These impairments in the intrinsic feedback system may lead to a further reduction in postural awareness.

Muscle fatigue, decreased proprioception and the stretching of the passive structures of the spine are time and cycle dependent (Howarth & Mastragostino, 2013; Taimela et al., 1999). In an animal study, repetitive flexion loading of the spine over a 60-minute period led to a reduction in electromyography (EMG) amplitude and median frequency (MF) measures in the first hour post-loading (Solomonow, 2012). This reduction in muscle activation was accompanied by increased laxity of the viscoelastic structures of the spine, which took seven hours to recover to pre-loading levels (Solomonow, 2012). Cyclic lumbar flexion loading has also been shown to reduce reflexive responses and lead to decreases in intrinsic spinal stiffness (creep) in human subjects at least 20 minutes after loading (Muslim et al., 2013). It has been suggested that viscoelastic stretch following cyclic end range lumbar flexion may reduce the proprioceptive input of spinal ligaments (Maduri & Wilson, 2009). This is evidenced by the reduction in lumbar proprioceptive acuity following repetitive flexion (Sanchez et al., 2006). This cascade of events could cause fatigue-related biomechanical changes in the lifting strategy and increased reliance on passive structures that are detrimental and increase the risk of injury to the spine.

2.6 Biofeedback and Movement Patterns

Biofeedback has been used for more than 50 years in rehabilitation to aid normal movement patterns after injury. Biofeedback is a form of psychophysiological self-regulation that has been defined as the use of appropriate instrumentation to bring physiological processes to the conscious awareness of one or more individuals (Ernst, 2003; Tate & Milner, 2010). Biofeedback has been referred to as extrinsic or augmented feedback that provides the individual with additional information, often in real-time, that would otherwise be unknown (Giggins, Persson, & Caulfield, 2013). Biofeedback can provide an individual with additional information if the intrinsic feedback system (sensory information from various intrinsic sensory receptors in muscles and joints) is compromised (Onate, Guskiewicz, & Sullivan, 2001).

External feedback usually involves the measurement of a biomedical variable(s) which is communicated to the individual with one of two strategies (Giggins et al., 2013). The first strategy involves direct feedback about the measured variable. For example, in the case of heart rate variability, a numerical variable is displayed on a device such as a watch (Giggins et al., 2013). The second strategy involves transformed feedback of a measured variable, where the measurements are used to control an adaptive auditory, visual, or tactile feedback method (Giggins et al., 2013). For example, an inclinometer worn on the belt can measure the inclination of the pelvis and can be set to alert the user if they tilt forward beyond a certain angle (Ribeiro et al., 2014).

2.6.1 Categories of Biofeedback

The majority of physical rehabilitation biofeedback research has focused on the effects of biofeedback therapy in the treatment of upper and lower limb motor deficits, predominantly in patients with neurological disorders (Ernst, 2003). Other areas of biofeedback research include, but are not limited to, temporomandibular disorders (Crider & Glaros, 1999), rheumatoid arthritis (Astin, Beckner, Soeken, Hochberg, & Berman, 2002), back pain (Van Tulder, Koes, & Bouter, 1997), and stroke rehabilitation (Moreland, Thomson, & Fuoco, 1998).

A systematic review of biofeedback used in physical assessment and rehabilitation (Giggins et al., 2013) identified two broad categories of feedback: 1) biomechanical; and 2) physiological. Biomechanical biofeedback includes measures of postural control, movement, and force while physiological biofeedback includes feedback of the neuromuscular, cardiovascular, and respiratory systems (Giggins et al., 2013). Table 2.2 provides a summary of the categories of biofeedback used in rehabilitation.

Table 2.2 Categories of biofeedback used in physical assessment and rehabilitation (adapted from Giggins et al. (2013)).

Categories of biofeedback	
Biomechanical	**Physiological**
Postural control	***Neuromuscular***
Inertial sensors	Electromyography
Accelerometers	Ultrasound imaging
Electrogoniometers	
Movement	***Cardiovascular***
3D motion analyses	Heart rate
Inertial sensors	Photoplethysmography
Camera-based systems	
Virtual reality	
Force	***Respiratory***
Force plate systems	Heart rate variability
Pressure biofeedback	

3D – three dimensional

2.6.2 Contemporary Biomechanical Biofeedback Methods for Spinal Motion

There are a number of traditional methods available for measuring and providing feedback on spinal motion including 3D motion analysis, radiographs, and magnetic resonance imaging (MRI) (Giggins et al., 2013; Mannion & Troke, 1999; Pearcy, 1985). Considering the risks associated with ionising radiation from X-rays (Thompson & Cullom, 2006) and the high cost associated with MRI (K. O'Sullivan, O'Sullivan, Dankaerts, & O'Sullivan, 2010), laboratory-based 3D motion analysis systems are a common alternative used to analyse spinal posture and movement (Trott, Pearcy, Ruston, Fulton, & Brien, 1996). While there will always be a degree of error due to skin movement, these surface-based marker systems have been shown to be valid and reliable in providing an accurate and detailed representation of the underlying spinal structure (Gracovetsky et al., 1995). Unfortunately, these devices are expensive, costly to operate and can be time consuming. Additionally, their lack of portability, cumbersome size, and need for visibility of skin markers often makes them unsuitable for use outside the laboratory environment (K. O'Sullivan et al., 2010). Therefore, the majority of research examining spinal posture and movement patterns in LBP has been performed in the laboratory environment rather than in social or occupational settings (Dankaerts, O'Sullivan, Burnett, & Straker, 2006). To perform research on spinal posture and movement patterns in an occupational or social setting, other, less invasive, technologies have evolved.

2.6.3 Wearable Biofeedback Technology

Advances in technology are making it cost effective to acquire valid and reliable measurements of posture using smaller, portable electronic devices that can measure spinal posture in real-time over prolonged periods (Mannion & Troke, 1999; McAlpine, Bettany-Saltikov, & Warren, 2009; Sheeran, Sparkes, Busse, & van Deursen, 2010). The available devices can broadly be categorized into: inertial sensors, fiber-optic goniometers, strain gauges, inclinometers, electromagnetic sensors, ultrasonic devices, and flexible electrogoniometers (K. O'Sullivan et al., 2010). The feedback provided by these devices can broadly be categorized into real-time and delayed. The real-time feedback can be in the form of audial, visual, vibratory, or a combination of these. The delayed feedback is normally in the form of summary feedback post-processing. Table 2.3 summarizes the range of devices that are currently (at the time of publication) implemented to monitor and provide postural feedback according to their measurement capabilities and feedback type. Inertial sensors that can monitor and provide biofeedback on spinal posture will be explored in more detail in Section 2.6.3.1.

Table 2.3 Categories of spinal posture biofeedback devices currently used in physical rehabilitation (adapted from K. O'Sullivan et al. (2010)).

Device	**Measurement**	**Feedback**	
		Timing	Type
Inertial sensors	3D kinematics through accelerometer, gyroscope and magnometer e.g. spinal posture, knee/hip angles	Real-time	Audial Visual Vibratory
Fibre-optic goniometers	Joint angles through changes in light path e.g. spinal posture	Delayed	Post-processing
Strain gauges	Strain on material at points of attachment e.g. lumbopelvic posture	Real-time	Audial Vibratory
Inclinometers	Spinal inclination in one or more planes e.g. lumbopelvic ROM	Delayed	Post-processing
Electromagnetic sensors	Joint angles through changes in relative angle of sensors	Delayed	Post-processing

Ultrasonic devices	Spinal posture determined by calculating distance between sensors placed on the spine.	Real-time	Audial Vibratory
Flexible electrogoniometers	Linear displacement converted into angular data e.g. knee/ankle ROM	Delayed	Post-processing

3D – three dimensional; ROM – range of motion

2.6.3.1 Inertial Sensors

Inertial sensors are one of the most commonly used devices to provide postural biofeedback (Ribeiro et al., 2014). Inertial sensors measure acceleration, angular velocity and gravitational acceleration (Schepers, 2009). Inertial sensors estimate 3D kinematic information of a body segment such as orientation, velocity, and gravitational force by integrating information from built in accelerometers, gyroscopes, and magnometers (Schepers, 2009). Inertial sensors have been used in a range of applications and can provide biofeedback in a variety of modalities including audial, tactile, and visual signals.

Inertial sensors have been used as a tool to provide valid and reliable feedback on LS posture (Ribeiro et al., 2014; Wong & Wong, 2008), and their small size make them discrete and easy to wear. For example, Intolo, Carman, Milosavljevic, Abbott, and Baxter (2010) used a single inertial sensor attached to the subject's belt to estimate lumbopelvic flexion. This device was found to be reliable in the measurement of lumbopelvic ROM and posture in a single session in a laboratory, and was validated against a traditional motion analysis system (Intolo et al., 2010).

Some studies have implemented two or more inertial sensors and placed them above and below the part of the spine to be measured. The Back Strain Monitor, for example, consists of two inertial sensors placed on the lumbopelvic region (Ronchi, Lech, Taylor, & Cosic, 2008). This device can monitor frontal, sagittal and coronal plane movement and has been shown to have good inter-rater reliability, with an intraclass correlation coefficient (ICC) of 0.93 and intra-rater reliability (ICC = 0.94) and is able to provide real-time postural biofeedback (Ronchi et al., 2008). Vignais et al. (2013) constructed a virtual skeleton by incorporating seven inertial sensors. This network of devices could monitor posture (including lumbopelvic angles), and provide feedback in real-time while the subjects performed simulated activities in a purpose built factory environment (Vignais et al., 2013). They concluded that inertial sensors were a practical and reliable method for measuring lumbopelvic posture in simulated working environments and they have the added capability of providing biofeedback (Vignais et al., 2013).

The consensus was that two or more inertial sensors are required to accurately measure lumbopelvic posture however this introduces more complexity and cost to such methods.

2.6.4 Biofeedback Parameters

Different methods have been used to provide biofeedback depending on the application (K. O'Sullivan et al., 2010). The content, timing, and frequency of biofeedback is considered important for optimizing motor learning (K. O'Sullivan et al., 2010). Ribeiro et al. (2011) conducted a systematic review of LBP and external feedback with a summary of the feedback characteristics provided in Table 2.4.

Table 2.4 Biofeedback content, timing and frequency characteristics (adapted from Ribeiro et al. (2011)).

Feedback characteristic	Definition
Content	
Programme feedback	Feedback related to the general pattern of movement.
Parameter feedback	Feedback related to a specific component (part) of the whole movement pattern.
Summary feedback	Feedback is pooled and provided after a specific number of trials.
Average feedback	Feedback provided refers to mean values (mean error or performance score) of a group of trials.
Bandwidth (error magnitude)	The amount of error that is considered to distinguish successful from unsuccessful trials.
Internal focus of attention	Feedback drives learner's attention to body movement characteristics.
External focus of attention	Feedback drives learner's attention to the effect of the movement.
Timing	
Concurrent feedback	Feedback is provided simultaneous to task execution.
Terminal feedback	Feedback is provided after task execution.
Immediate	Feedback is provided immediately after task execution;

Delayed	Feedback provision is delayed until the end of the task execution.
Frequency	
Constant	Feedback is provided at every trial.
Reduced	Feedback is provided for a fraction of trials (e.g. 30%).
User-controlled	Feedback provision depends on learner's decision.

2.6.4.1 Content Characteristics

Motor control learning is task specific and, therefore, functional training is considered optimal for learning rather than training individual components of the task (Shumway-Cook & Woollacott, 2007; van Vliet & Wulf, 2006). During motor control learning feedback can be provided about the overall movement being trained, or about the individual components of that movement (Schmidt & Wrisberg, 2008). Programme feedback provides error information about the fundamental pattern of movement (or motor programme) while parameter feedback provides error information about changeable features such as amplitude, speed and force (Schmidt & Wrisberg, 2008). Programme feedback is therefore considered the most optimal method for learning a new motor task over parameter feedback (Ribeiro et al., 2011), particularly during the early stages of skill acquisition (Schmidt & Wrisberg, 2008). However, the majority of LBP studies have chosen to implement parameter feedback rather than the more desirable programme feedback (Ribeiro et al., 2011). One reason for this could be that many physiotherapists believe that LBP patients need to improve certain movement features to improve the overall quality of such movements (Ribeiro et al., 2011). Programme feedback has, however, been used for postural monitoring during activities of daily living (Ribeiro et al., 2014; Vignais et al., 2013). Parameter feedback has been used to provide feedback about the timing of contraction of the transverse abdominis (TA) muscle in LBP rehabilitation (Hodges, 1999) and modulation of spinal muscle co-contraction while increasing spinal loads (Marras, Davis, Heaney, Maronitis, & Allread, 2000).

The amount of information provided is considered important during feedback. Summary feedback provided at the end of a number of trials appears optimal for motor learning (Schmidt, Lange, & Young, 1990). In addition, an optimal number of trials is often considered prior to the provision of feedback (Schmidt et al., 1990). It has been shown that as the complexity of a task increases, and previous motor experience associated with the task decreases, the number of trials to be included in summary feedback should be reduced (Guadagnoli & Lee, 2004).

2.6.4.2 Timing and Frequency Characteristics

There is conflicting evidence on the timing and frequency of feedback, where some studies have found improvements in posture (Ribeiro et al., 2014; Worth, Henry, & Bunn, 2007) and muscle activation (Worth et al., 2007), while others have found no improvements in these areas (Henry & Westervelt, 2005; Vignais et al., 2013). Ribeiro et al. (2014), for example, investigated the effects of real-time LS posture feedback during an occupation based activity. Participants received immediate feedback if their LSF angle exceeded 45° during normal working activities that resulted in a significant reduction in LSF (Ribeiro et al., 2014). Another example of successful real-time feedback can be seen in rehabilitative ultrasound imaging using concurrent feedback which was shown to enhance the contraction of transverse abdominus (TA) (Worth et al., 2007). In contrast, Henry and Westervelt (2005), for example, found that rehabilitative ultrasound imaging did not enhance the ability of their participants to perform the abdominal drawing in the exercise. Vignais et al. (2013) found no differences in either concurrent or terminal feedback where participants received real-time postural feedback while performing lifting tasks in a simulated factory

The majority of biofeedback studies related to posture included bandwidth feedback, or error magnitude feedback as part of their feedback protocols (Breen et al., 2009; Lou et al., 2012; Magnusson et al., 2008; Vignais et al., 2013; Wong & Wong, 2008). Bandwidth feedback refers to the amount of error that distinguishes successful and unsuccessful trials (Ribeiro et al., 2011). Bandwidth biofeedback can enhance motor learning if participants are aware that non-provision of feedback means performance was correct or within a predetermined error tolerance (Butler, Reeve, & Fischman, 1996). Bandwidth size during motor task trials can also make a difference in motor outcomes, with larger bandwidths (10%, when compared to 0 to 5%) showing better outcomes (Smith, Taylor, & Withers, 1997).

2.7 Summary of the Narrative Literature Review

In summary, LBP is a common and costly disease affecting a large proportion of the population. Causes are believed to be multifactorial and biomechanical risk factors appear to play a prominent role within occupational settings. These include the magnitude of forward trunk flexion, the time spent in flexed trunk postures and repetitive trunk flexion. During a fatiguing task, such as repetitive lifting, the body's intrinsic feedback system may be adversely affected leading to changes in postures that may increase the risk of LBI. Furthermore, fatigue failure of the spine during repetitive loading occurs more rapidly when the spine is flexed.

Biofeedback has been shown to be an approach that can correct posture and has been used as an intervention and rehabilitation tool to prevent and treat LBP, by augmenting the intrinsic feedback system and providing increased postural awareness, particularly during a fatiguing task.

The majority of biofeedback research in low back rehabilitation has primarily targeted muscle recruitment, as opposed to postural feedback during functional tasks. Those studies that have used postural biofeedback have mainly implemented delayed feedback in the form of post-processing summary information about posture. The studies that have implement real-time postural feedback in physical rehabilitation have used differing protocols and equipment to provide feedback. Most of these studies used trunk inclination rather than lumbar motion and often use single devices to estimate spinal posture. Since the majority of spinal injuries are related to the lower back, it would be more prudent to measure LS posture directly.

With advances in technology it is becoming more affordable and realistic to monitor posture and provide real-time biofeedback with devices such as inertial sensors. More recent research indicates that inertial sensors are a practical and reliable measure of LS posture outside of the laboratory and have the added capability of providing real-time biofeedback (K. O'Sullivan et al., 2010). It remains unclear, however, whether real-time feedback on lumbar position alters motion and loading of the lumbar spine during repetitive functional tasks where fatigue may occur. This prompted the need to perform a systematic review of the literature to investigate the evidence for the use of real-time biofeedback in spinal posture. This follows in Section 2.8.

2.8 Systematic Review: To Investigate the Effectiveness of Real-time Biofeedback as an Approach to Affect Changes in Spinal Posture

2.8.1 Aim

Based on the findings presented in the narrative literature review, it is still unclear whether real-time postural feedback modifies motion and loading of the spine. The following systematic review was conducted to determine the level of clinical evidence for real-time postural biofeedback as an approach to changing spinal posture.

2.8.2 Method

2.8.2.1 Literature Search

Eight databases were searched (Scopus; Medline; CINAHL Plus; Academic Search Premier; SPORTDiscus; Ergonomics Abstracts; PubMed; PEDro; Cochrane). An example of the search terms used is shown in Appendix A. Selection was based on the inclusion/exclusion criteria as outlined below. Following the exclusion of duplicates, one independent reviewer (YN) evaluated all articles that were identified in the search. Studies that did not meet inclusion criteria (see below) were initially excluded on title, then by abstract, and finally on a review of the full text. When necessary, two additional independent reviewers (MB and GM) were consulted about the suitability of study's inclusion. All articles were downloaded into Endnote X7 software.

2.8.2.2 Inclusion/exclusion Criteria

This review was restricted to peer-reviewed randomized and non-randomized controlled trials published in journals. Due to the limited number of studies on the lumbar spine, the whole spine was included in this review.

Studies were only included if:

- Participants were 18 years of age or over.
- The primary intervention involved real-time postural biofeedback and included feedback related to the spine.
- The feedback device was wearable and operated wirelessly.
- Feedback was in the form of audial, vibratory, visual feedback, or a combination of these.
- The intervention was compared either to a baseline measure or a control group, in the case of randomized controlled trials (RCT).

Studies were excluded if:

- They were animal studies.
- They were not published in English.

- They were not available in full text format.
- Participants had any neurological condition, including previous stroke.
- Participants had an acquired brain injury.
- Participants had multiple sclerosis.
- Participants had any other condition that could adversely influence their central or peripheral nervous systems.

2.8.2.3 Data Extraction

One reviewer (YN) extracted information from each study using a standardized data extraction form. Information recorded from studies included: study design; participant characteristics; inclusion and exclusion criteria of participants; postural measuring device; intervention protocol; feedback parameters; and main findings. This was performed independently by one reviewer (YN), who met to reach agreement on reported information with the two other reviewers (MB and GM). Descriptive statistics were used to summarize the participants, interventions and outcome measures.

2.8.2.4 Quality Assessment

All studies included were critically appraised by three independent reviewers (YN, MB and GM) using the modified Downs and Black (DB) critical appraisal tool (see Appendix B), which has been shown to have good test-retest, and inter-rater reliability (Downs & Black, 1998). This enabled measurement of study quality, and internal and external validity. A total score out of a maximum of 28 was allocated to all RCTs and a total score out of a maximum of 24 was allocated to all quasi-experimental studies. Question 5 could score 0-2 and the rest of the questions 0-1, depending on the information presented. Due to the non-random nature of quasi-experimental studies, they were not rated on blinding of assessors or participants, random assignment, or concealment of group allocation. RCT were classified as strong methodological quality if the DB score was ≥21, moderate if it scored between 14 – 20, and low if it scored <14 (Mani, Milosavljevic, & Sullivan, 2010). The quality of quasi-experimental studies were rated as strong, moderate, or low if they scored ≥18, between 12 and 17, or < 6 respectively (Mani et al., 2010).

2.8.2.5 Level of Evidence of Included Studies

The Grading of Recommendations Assessment, Development and Evaluation (GRADE) checklist was used to establish the level of clinical evidence of the included studies (Guyatt, Oxman, Schünemann, Tugwell, & Knottnerus, 2011; Ma & Bai, 2014).This checklist takes into account study type (RCT or quasi-experimental), quality (based on blinding and allocation, follow-up and withdrawals, and scarcity of data), consistency (the degree of consistency of effect between studies), directness (generalizability of outcome from studies to the population of interest), and effect size across studies. The GRADE Working Group guidance identifies that the inclusion of quasi-experimental studies may be warranted in addition to RCTs, if only limited or no RCT are available (O'Neil et al., 2014). To establish the level of clinical evidence from the data set, all studies were grouped into RCT and non-RCT.

2.8.3 Results

2.8.3.1 Study Selection

The search returned 2020 studies, 66 of which were deemed eligible for full text review (Figure 2.2). Of these, 58 studies were excluded, leaving eight studies meeting the inclusion/exclusion criteria. The reasons for exclusion were: no experimental measure in the study (N = 20), no feedback provided on posture (N = 18), feedback was not in real-time (N = 8), there was no kinematic outcome measure (N = 6), the publication was a conference abstract (N = 5) or a text book chapter (N = 1). The characteristics of these studies are summarized in Table 2.5.

2.8.3.2 Study Types

Of the eight articles included, four were RCT (Çelenay et al., 2015; Magnusson et al., 2008; Ribeiro et al., 2014; Vignais et al., 2013) and four were quasi-experimental design (Breen et al., 2009; Dean & Dean, 2006; Lou et al., 2012; Wong & Wong, 2008). In three of the RCTs (Çelenay et al., 2015; Ribeiro et al., 2014; Vignais et al., 2013), the control group received no feedback. In Magnusson et al. (2008) and Çelenay et al. (2015) the control group received standard care in the form of back care programmes focusing on ROM and physical activity. Ribeiro et al. (2014) included two intervention groups, an intermittent feedback group that received feedback alternative weeks, and a constant feedback group receiving fulltime feedback throughout the trial period.

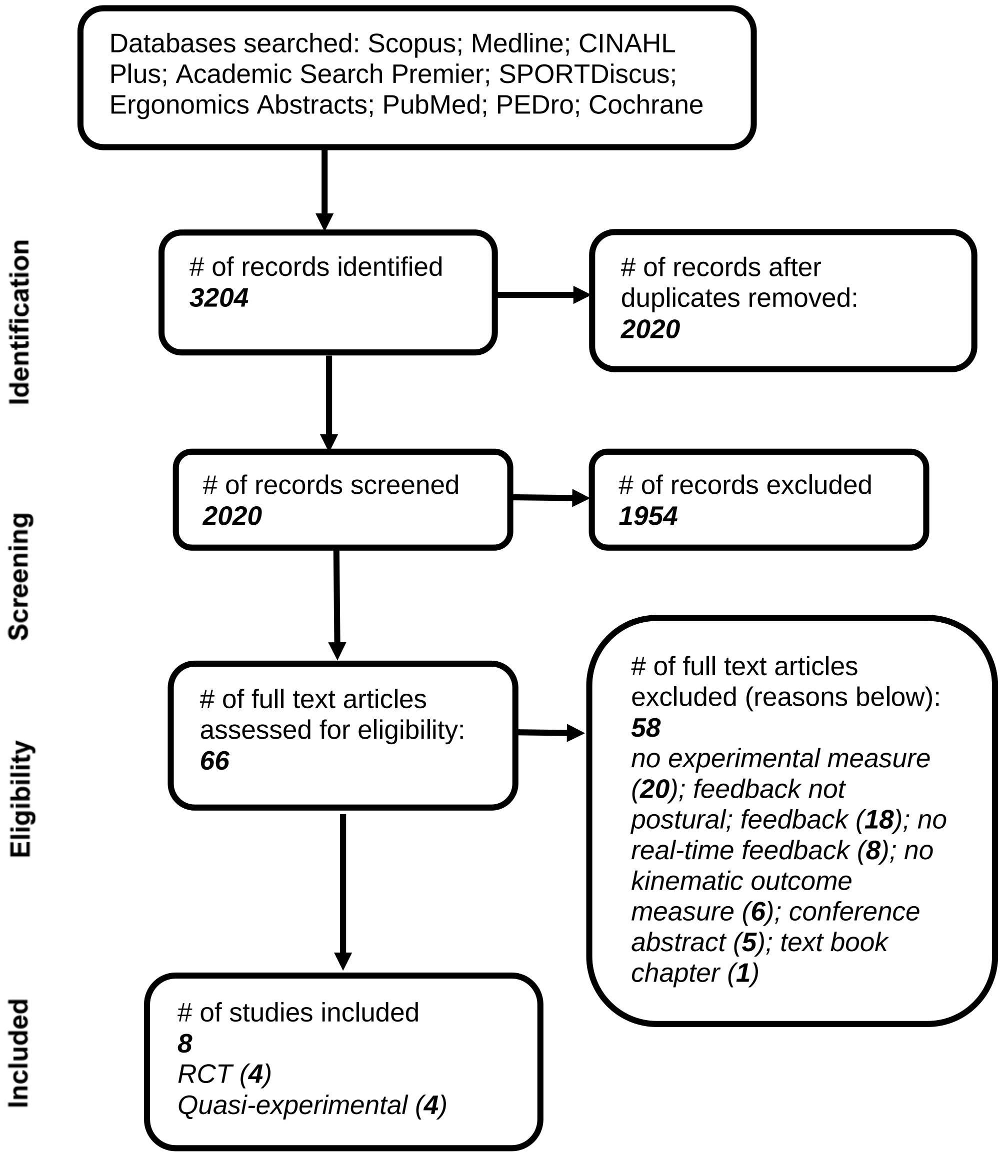

Figure 2.2 Identification, screening and selection of articles

Table 2.5: The Main characteristics of articles included in this review.

Study	Participants	Inclusion Criteria	Exclusion Criteria	Biofeedback device	Protocol	Biofeedback Method	Findings
Çelenay et al. (2015) RCT DB = 15	N = 48, university students, 24 CG, 24 BF, mean age = 20 ± 1.0 years, weight = 52.4 ± 11.6kg.	Healthy between the ages of 18-25 years, sedentary for more than 12 months.	Systemic pathology, musculoskeletal injury, any medication 3 months prior to the study.	BackTone Biofeedback Posture Trainer consisting of a webbing harness with an electronic sensor.	8 weeks, 3 days per week, 20 minutes per day.	Audial or vibratory feedback when: • Slouching.	A significant reduction in thoracic curvature compared to baseline BF (Pre: 33.91±2.12; Post: 29.66 ± 2.35); ($p < 0.05$). Significant difference between groups ($p < 0.05$) in thoracic curvature.
Riberio et. al. (2014). RCT DB = 16	N = 62, health care and administrative workers. 18 controls (CG), 25 intermittent feedback (IFG), 19 constant feedback (CFG), mean age = 49.6, mean height = 1.63m, mean weight = 73.6kg.	Able to work for > 20 hours per week without physical problems e.g. pain or discomfort.	Unable to undertake their regular work-related activities due to NSLBP or worked < 20 hours per week.	Single accelerometer (Spineangel) attached to waist belt to measure postural changes in the sagittal and coronal planes.	6 weeks during working hours. CG – no feedback IFG – feedback alternating weeks CFG – permanent feedback.	Audial feedback when: • > 45˚ of lumbo-pelvic (LP) flexion. • Twice or more per minute. • > 5 seconds.	CFG - significant reduction in LP flexion compared to baseline: ($t = -2.25, p = 0.03$, ES = 0.51). CFG – significant reduction in feedback frequency per hour: (pre = 2.29±2.49 $p = 0.03$; post = 1.32±1.27 $p = 0.03$). No significant differences between groups LP flexion.
Lou et al. (2012) Quasi-experimental DB = 10	Four male volunteers (28±5 years)	Healthy	None	Two accelerometers attached to a Smart harness worn on the upper body (T1 to T12) measuring relative trunk angle.	4 consecutive days, 3 h per day. D1 (baseline normal sitting kyphotic angle) and D2 with no feedback. D3 and D4 with feedback.	Vibratory feedback when: • Kyphotic > 5˚ from baseline • > 2 seconds.	Reduction of 8˚±21˚ ($p < .05$) kyphotic angle from D1 to D4.
Vignais et al. (2013) RCT	N=12, students. 6 control (CG),	Male	None	7 accelerometers (wireless) used to calculate a whole body and segmental RULA	Simulated standardised factory task/s scenario in a SmartFactory living lab.	Audial feedback when: • Global score = 7 • Lasting > 0.5s or if the score was 5-6	Significant improvement in RULA score: CG (4.35±0.54)

DB = 12	6 with feedback (FG) mean age = 22.5 years±2.5 years, mean weight 76.6±12.7kg, height 1.8±0.06m			score (1- low risk to 7 - high risk).		• Lasted at least 5s • A visual cue related to local scores was given to the user via the STHMD.	FG (3.95±0.83) ($p < .05$) Local scores (time spent in at risk posture): Neck (FG = 12.24±15.89%; CG = 34.03±10.8; $p < .05$) Significant differences between groups in mean RULA score ($p < 0.05$).
Breen et al. (2009) Quasi-experimental DB = 9	N = 6, computer users	Seated computer users as part of job/study.	No history of neck or back pain.	Single accelerometer placed on C7 measuring relative kyphotic angle connected to the desktop PC via a microcontroller.	Two 5 hour sessions with and without feedback.	Visual (GUI) and audial feedback when: • > 40˚ flexion of C7 movement from baseline.	Significant reduction in time spent in undesirable posture. Pre 35.7% ±15.3% to post 6.5% ± 9.6% ($p < .05$).
Magnusson et al. (2008) RCT DB = 17	N = 47, randomized into standard or biofeedback groups	Age 20-70, CLBP with or without leg referral, fit to attend rehab programme	Fracture, tumour, infection, knee or hip arthritis, severe psychopathologic conditions.	Goniometer (BackTracker), measuring relative spinal angle in relation to the pelvis mounted on a harness between T6 and LS joint.	Five 1 hour sessions held on consecutive weeks. Progressive postural exercises were performed using a GUI.	Visual (GUI), audial and success rate reports in order to: • Progressively increase the ROM and duration of various spinal movements. • Success rates reports had to exceed 85% for each task in order to progress.	Significant improvement in ROM and speed of movement in biofeedback group. Extension angle: pre 9.67˚, post 16.39˚,($p < .043$). Extension angular velocity: pre 3.54˚/s, post 6.28˚/s ($p < .028$) No significant differences between groups.
Wong & Wong (2008) Quasi-experimental DB = 10	N = 5, 4 female and 1 male students, mean age 25.2±4.8 years,	Normal subjects	None	Three accelerometers/ gyroscopes attached to a smart garment at T1/T2, T12 and S1.	2 hours per day during leisure time at home for 4 consecutive days. Day 1 and 4 with no feedback. Day 2 and 3 with feedback.	Audial feedback when thoracic or lumbar posture: • > one minute ± 10˚ tolerance on day 2	Significantly reduction in lumbar flexion posture. Day 1 – 23.1˚±11.3˚ Day 2 – 8.2˚±3.3˚ Day 3 – -0.7 ˚±7.4˚

	mean height 1.7±0.09m, mean weight 50.5±7.2kg.				Thoracic and lumbar curvature were estimated.	• > one minute and ± 5˚ tolerance on day 3.	Day 4 – 14.5˚±15.8˚ (p = .039)
Dean & Dean (2006) Quasi-experimental DB = 11	N = 25, golfers, 13 male, 12 female, mean age = 48 ±11.y	Able to remove golf bag from car independently.	LBP in the last 3 months, golf handicap exceeds 36.	Proprietary device (OPM) employing a spring-loaded displacement pin connected to a data logger and PC measuring changes in sagittal plane movement placed over L5.	Removing golf bag from car. D1: Perform task once with no feedback; D2: perform task 3 times with biofeedback; D3: perform task once with no biofeedback.	Audial and vibratory feedback when: • > 20˚ flexion from upright standing (baseline) at L5.	A significant difference in the number of times the OPM was triggered (pre: 5.16±4.74; post: 2.32 ±1.63 (p < .004)) A significant difference in the duration of time the OPM was triggered (pre: 39.04s±25.49s; post 13.76±12.12 (p < .001)).

BF – biofeedback group; CG – control group; IFG - intermittent feedback; CFG - constant feedback group; DB – Downs and Black quality score; RCT – randomised control trial; LP – lumbopelvic; NSLBP – non-specific lower back pain; LBP – lower back pain; OPM - orthosense posture monitor; D – day; PC – personal computer; GUI -graphical user interface; RULA – Rapid Upper Limb Assessment; STHMD – see-through head-mounted display; D1 – day 1; D3 – day 3; ROM – range of motion

2.8.3.3 Outcome Measures

All studies included direct or indirect kinematic outcome measures of the spine. One study investigated pelvic motion (Ribeiro et al., 2014). Two studies focused on the lumbar spine kinematics (Dean & Dean, 2006; Magnusson et al., 2008), while two studies assessed thoracic and lumbar kinematics (Çelenay et al., 2015; Wong & Wong, 2008). Breen et al. (2009) concentrated on cervical kinematics and Vignais et al. (2013) on whole body kinematics, including the lumbar spine, in order to calculate a global posture score.

2.8.3.4 Methodological Quality

Three studies were of moderate methodological quality and five of low methodological quality (Table 2.6). One of the major weaknesses with the RCT studies was the risk of bias (Magnusson et al., 2008; Ribeiro et al., 2014; Vignais et al., 2013) where only one study (Çelenay et al., 2015) blinded assessors and only one study (Ribeiro et al., 2014) blinded participants. Additionally, three studies did not clearly describe their hypotheses (Lou et al., 2012; Vignais et al., 2013; Wong & Wong, 2008) and only two studies clearly described confounding variables (Magnusson et al., 2008; Ribeiro et al., 2014).

2.8.3.5 Participants

The total number of participants provided with biofeedback was 137 and 71 acted as controls. All but one study (Magnusson et al., 2008) recruited healthy adult participants from a specific populations of interest, i.e. golfers (Dean & Dean, 2006); computer workers (Breen et al., 2009); healthcare workers (Ribeiro et al., 2014); and university students (Çelenay et al., 2015; Vignais et al., 2013).

2.8.3.6 Feedback Interventions

2.8.3.6.1 Protocols

Feedback interventions varied considerably across the studies in the number of times each participant received feedback, the number of days between interventions, and the follow up time post intervention. For example, Dean and Dean (2006) implemented biofeedback while performing specific tasks on one day, and measured spinal kinematics the following day without feedback. Another study measured posture and provided feedback on the same day while participants were performing real world tasks in a simulated laboratory (Vignais et al., 2013).

Table 2.6: Quality scores of studies using Downs and Black critiquing tool.

	Hypothesis described	Main Outcomes described	Participant characteristics	Intervention described	Confounders described	Findings described	Random variability estimates	Adverse events reported	Participants lost to F/U	Probability values	Participants asked, represent population	Participants participated, represent population	Activities and surroundings representative	Participants blinded	Assessors blinded	Data dredging made clear	Adjust for length of F/U	Statistics appropriate	Compliance with intervention	Outcomes reliable and valid	Participants all from same group	Participants recruited over same time period	Randomised to different groups	Group assignment concealed	Adjustment made for confounders	Participants lost to F/U accounted	Power calculation?	**Total**
RCT																												
Çelenay 2015	1	1	1	1	0	1	0	0	1	0	1	1	1	0	1	1	0	0	1	0	1	0	1	0	0	1	0	**15**
Ribeiro 2014	1	1	1	0	2	0	1	0	0	1	0	0	1	1	0	1	0	1	1	0	1	0	1	0	1	1	0	**16**
Vignais 2013	0	1	1	1	0	1	0	0	1	0	0	0	1	0	0	1	1	0	0	0	1	1	1	0	0	1	0	**12**
Magnusson 2008	1	1	1	1	1	1	0	0	1	1	1	1	1	0	0	1	1	1	0	0	1	1	1	0	0	0	0	**17**
Quasi-experimental																												
Lou 2012	0	1	0	1	0	1	0	0	1	0	0	0	1	NA	NA	1	1	0	0	1	1	0	NA	NA	0	1	0	**10**
Breen 2009	1	1	0	1	0	0	1	0	1	0	0	0	1	NA	NA	1	0	0	0	0	1	0	NA	NA	0	1	0	**9**
Dean 2006	1	0	0	1	0	1	1	0	1	1	0	0	1	NA	NA	1	0	1	0	0	1	0	NA	NA	0	1	0	**11**
Wong 2008	0	1	0	1	0	1	1	0	1	1	0	0	1	NA	NA	1	0	1	0	0	0	0	NA	NA	0	1	0	**10**

F/U – follow up; NA – not assessed

Three of the eight studies monitored posture and provided feedback for at least five consecutive days while performing activities of daily living (Breen et al., 2009; Magnusson et al., 2008; Ribeiro et al., 2014).

2.8.3.6.2 Equipment

Five of the eight studies implemented inertial sensors to measure spinal posture (Breen et al., 2009; Lou et al., 2012; Ribeiro et al., 2014; Vignais et al., 2013; Wong & Wong, 2008). The number of sensors used varied from single devices in two studies (Breen et al., 2009; Ribeiro et al., 2014) up to seven devices in one study (Vignais et al., 2013). Other devices included electronic sensors (Çelenay et al., 2015) that measure strain on a spinal harness worn by participants and one study (Magnusson et al., 2008) implemented an electronic goniometer to measure spinal posture.

2.8.3.6.3 Kinematics

Five studies measured sagittal plane kinematics of the spine (Breen et al., 2009; Çelenay et al., 2015; Dean & Dean, 2006; Lou et al., 2012; Magnusson et al., 2008) and only two studies measured coronal plane kinematics (Ribeiro et al., 2014; Wong & Wong, 2008). Vignais et al. (2013) monitored the whole body posture, including the spine, with a network of seven accelerometers.

2.8.3.6.4 Feedback

There was no consistency between studies in the type and method of feedback provided. Feedback types included audial (Ribeiro et al., 2014; Wong & Wong, 2008), audial and visual in the form of a graphical user interface (GUI) of spinal posture (Breen et al., 2009; Magnusson et al., 2008), vibratory (Lou et al., 2012), audial and vibratory (Çelenay et al., 2015; Dean & Dean, 2006) and a combination of audial, video and virtual reality (Vignais et al., 2013).

All studies included bandwidth feedback, but this varied across studies with different levels of performance or error magnitude thresholds. For example, Wong and Wong (2008) provided feedback if thoracic or lumbar postures were outside the neutral standing position for longer than one minute with a tolerance of ± 10˚ on Day1 and which decreased in magnitude to ± 5˚ tolerance on Day 2. In another study, feedback was given if the deviation in magnitude was greater than 5º of the participant's upright standing kyphotic angle for a period of more than 2 seconds (Lou et al., 2012). All studies had different threshold values at which feedback was initiated, for example Ribeiro et al. (2014) provided feedback at or above 45° of lumbar flexion and Dean and Dean (2006) provided feedback if their participants exceeded 20° of lumbar flexion.

All studies provided programme feedback, or feedback of the whole task, with an external focus of attention (on spinal posture). Thus, feedback was designed to drive the learner's attention to the effect of the whole movement. Magnusson et al. (2008) provided an external focus of attention where biofeedback was provided on the spine relative to the pelvis while performing a series of movements. Feedback was given during functional movements, for example, when leaning forward, to guide the participants to achieve the overall goal of reduced spinal flexion (Magnusson et al., 2008).

2.8.3.7 Effectiveness of Real-time Postural Biofeedback

All studies found feedback improved the ability of participants to maintain posture within the designated threshold limit they were prescribed. All studies found significant improvements in posture from the baseline in the groups that received biofeedback. Only two RCT studies found significant differences between the intervention and control groups (Çelenay et al., 2015; Vignais et al., 2013) post intervention. Only one study investigated the long term effects of external feedback on posture (Magnusson et al., 2008). The authors found that the positive outcomes associated with the biofeedback intervention were significant and were maintained at six months follow up. One study found that over a four-week period, constant feedback was more beneficial in maintaining posture within the preferred ROM, compared to intermittent feedback or no feedback (Ribeiro et al., 2014). Overall, RCT provided a low level of clinical evidence for the use of real-time postural biofeedback when compared to no feedback (GRADE score 2) (Table 2.7). There was a very low level of evidence for real-time postural biofeedback based on quasi experimental studies (GRADE score 1). The primary reason for low grade scores was due to the small effect size and the inconsistency between studies or the absence of reporting the effect size in other studies.

Table 2.7: Level of clinical evidence for real-time postural biofeedback interventions based on the GRADE rating system.

	Type of study	Quality	Consistency	Directness	Effect size	GRADE score
RCTs	+4	-2	0	0	0	**2**
Quasi Experimental Studies	+2	-2	+1	0	0	**1**

The GRADE score: high (at least 4 points overall), moderate (3 points), low (2 points), and very low (one or less).

2.8.4 Systematic Review: Discussion

There was a low level of clinical evidence to support the use of real-time postural biofeedback to modify spinal posture. All studies included in this review reported significant improvements in the ability to maintain optimal spinal postures with real-time biofeedback compared to no feedback or a control group. These results are in accordance with a previous systematic review that reported that biofeedback was an effective modality in physical rehabilitation training (Giggins et al., 2013). This review had a wide scope, however, and investigated both biomechanical feedback methods including force output, measurement of movement and postural control, and physiological feedback methods including neuromuscular, cardiovascular and respiratory feedback.

According to the GRADE system, the RCT group of studies in this review provided stronger support for the use of real-time biofeedback for the monitoring and improvement of spinal posture compared to the evidence provided by the controlled trials group. The main reason for this is due to the fact that RCT studies start with a higher overall score of four in the GRADE rating system (Table 2.7) compared to the initial score of two for the controlled trials and not necessarily due to the higher consistency or increased directness of the RCT group.

The overall low quality of the articles was partly due to the quasi-experimental design of four studies and the lack of a control group. The risk of bias was evident in the four studies that did have an intervention and control group, as none of the assessors or participants were blinded or their group allocation concealed. All studies had relatively small numbers of participants, further reducing their overall quality and generalizability to the wider population. Additional methodological weaknesses of the included studies were, the lack of clear description of confounding variables, and some studies failed to report the number of participants that were lost to follow-up or the reasons why.

Although the protocols varied between studies, there are overriding similarities in the type of feedback used. All studies delivered feedback within set bandwidths, some had larger error magnitudes compared to others. The evidence suggests that larger bandwidths could be associated with better motor outcomes particularly in terms of retention of motor skills (Smith et al., 1997).

Contrary to motor learning theory, that intermittent feedback is the optimal extrinsic feedback strategy (Ikegami, Hirashima, Osu, & Nozaki, 2012), this review found that intermittent feedback was not as effective as concurrent real-time feedback. A recent study has revealed that concurrent feedback can be effective if the motor task is complex (Sigrist, Rauter, Riener, & Wolf, 2013).

The neurological mechanisms that underlie the success of biofeedback training are not clear (Huang et al., 2006). According to Basmajian (1982), there are two possibilities: either new neural pathways are formed, or a supplementary feedback loop recruits existing central and peripheral neural pathways. Wolf (1983) argued that biofeedback activated unused or underused neural connections in motor execution and, with practice, new sensory engrams can be established to be used later without any feedback. Therefore, biofeedback may lead to improvements in neural plasticity by engaging auxiliary sensory inputs and could be used as a viable clinical tool for postural rehabilitation.

Biofeedback threshold values, or the values at which feedback was given, varied across studies with limited justification to support the reasons for the chosen values. One study made reference to the concept of repetitive lifting in a flexed lumbar posture leading to increased risk of injury and LBP (Ribeiro et al., 2014), as outlined in Section 2.5. None of the studies, however, implemented this concept described by Dolan, Earley, et al. (1994) and McGill (2015) that links increased risk of LBP with increased amounts of end-range lumbar flexion and increased time spent in flexed postures. Furthermore, there is a lack of research on high risk spinal ROM, as described in Section 2.5, and when to provide biofeedback accordingly to mitigate such risk.

It is not clear from the included studies how long the effects of postural biofeedback are maintained or how soon after the initial programme individuals would require postural awareness re-training, as only one study (Magnusson et al., 2008) reported long term results after 26 weeks.

2.8.5 Systematic Review: Conclusions

Whilst there are consistent findings to support the use of real-time biofeedback to change spinal posture the overall clinical evidence is not rigorous enough. This is due to a small number of low quality studies available in the literature to support this theory. Whilst some literature has investigated the effects of feedback during daily activities, no studies assessed the influence of biofeedback during repetitive or fatiguing manual handing tasks, where lifting strategies might change to a more flexed spinal posture (Dolan & Adams, 1998; Potvin et al., 1991). The studies investigated lumbar, thoracic and cervical spinal posture in the sagittal plane in a wide variety of activities such as sitting, standing and lifting. Larger randomized controlled and epidemiological studies are required to determine threshold values for spinal posture and to discriminate between high, medium, and low risk postures. This was the motivation to conduct an experimental study to address some of the limitations in the literature.

Chapter 3: Aims, Objectives and Hypotheses

3.1 Aims

The aim of this study will be to investigate the effects of real-time biofeedback on lumbar postural control and lifting strategy during a repetitive lifting task. A secondary aim will be to evaluate lower back and lower limb joint loading in response to real-time biofeedback.

3.2 Objectives

The objective of this study was to measure lumbar, hip and knee kinematics and kinetics during a repetitive lifting task under two conditions (with biofeedback and without biofeedback). Wireless inertial sensors provided a continuous measurement of LS angle and biofeedback was provided should the LS angle exceed 80% of maximum flexion. 3D motion analysis and ground reaction forces enabled the measurement of joint angles and moments, and passive loading on the lumbar spine. RPE was measured as an indication of fatigue.

3.3 Hypotheses

The following null (H0) and alternative hypotheses (H1) were developed:

1. H0: There will be no difference in LS flexion during a repetitive lifting task as a result of biofeedback.

   H1: Biofeedback will affect changes in LS flexion during a repetitive lifting task.

2. H0: There will be no difference in lower limb kinematics and kinetics during a repetitive lifting task as a result of biofeedback.

   H1: Biofeedback will affect changes in lower limb kinematics and kinetics during a repetitive lifting task.

3. H0: There will be no difference in the passive loading of the lumbar spine during a repetitive lifting task as a result of biofeedback.

   H1: Biofeedback will affect changes in passive loading of the lumbar spine during a repetitive lifting task.

4. H0: There will be no difference in perceived physical exertion during a repetitive lifting task as a result of biofeedback.

H1: Biofeedback will affect changes in perceived physical exertion during a repetitive lifting task.

Chapter 4: Experimental Study to Investigate the Effect of Real-time Biofeedback on Lumbosacral Posture during a Repetitive Lifting Activity

4.1 Introduction

This chapter describes the methods used to investigate the hypotheses of this study. Firstly, the study design will be described followed by the recruitment process for participants, including participant selection. Secondly, the independent variables will be defined and a detailed description provided of the kinetic and kinematic motion analysis variables. The experimental procedure will then be described along with data processing methods and statistical analysis.

4.2 Methods

4.2.1 Study Design

A participant-blinded, randomized controlled trial was used to investigate the effect of real-time biofeedback on LS posture during a repetitive lifting activity. Ethical approval was gained from the Auckland University of Technology Ethics Committee (AUTEC) (see Appendix C).

4.2.2 Repetitive Lifting Task

Participants were required to lift and lower a 13kg box (Figure 4.1) at a frequency of 10 lifts per minute for up to 20 minutes. The box was 30 x 25.5 x 25 cm (length/width/height) and was held by two handles that were cylindrical in shape (2.8cm in diameter) which extended 6cm from either side of the box, at a height of 17cm from its base. During the lifting task participants were instructed to maintain their grip on the box and lift the box to an upright standing position with their arms and elbows extended and the box resting against their thighs. On lowering the box, participants were instructed to rest the box on the platform while maintaining a hold of the handles. An electronic metronome provided an audible cue at a frequency of 20 times per minute designating the point at which to commence the lift and lower. Participants were not informed about the number of lifts to perform or how long the lifting task would last, but were verbally encouraged to continue lifting as long as possible. Participants could stop at any time if they were fatigued or if they had completed 20 minutes. During the lifting and lowering task participants were required to maintain a fixed, symmetrical foot position with each foot on a force platform. They were instructed to position their feet as close to the raised platform as possible without touching it. Throughout the lifting task, participants were reminded of these instructions.

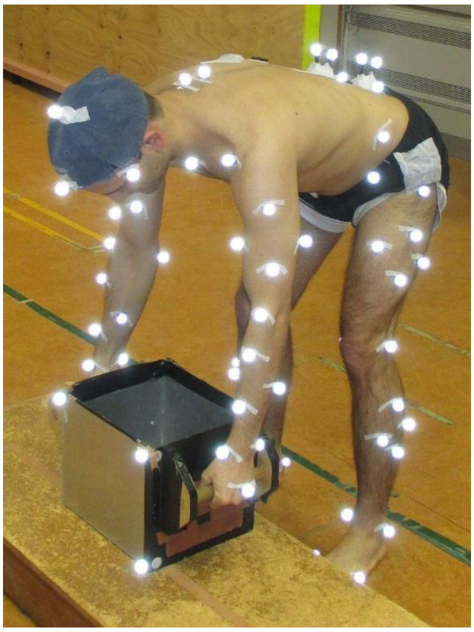

Figure 4.1 A participant performing the lifting task.

4.2.3 Participants

Participants were invited to participant if they met the following inclusion/exclusion criteria:

Inclusion criteria:

- Male
- Aged between 18-35 years old.
- Spoke and understood English.
- Self-reported to be medically fit and healthy.
- Able to attend one, three-hour laboratory session at the Health and Rehabilitation Research Institute (HRRI) at AUT.
- Were not experienced in manual handling or performed manual handling regularly.

Exclusion criteria:

- Experienced a back injury or back related complaint in the last six months.
- Undergone spinal surgery.
- Any cardiovascular or neurological conditions.
- Any musculoskeletal injury at the time of the study.

Participants were recruited via poster advertisements on student and staff notice boards at the AUT's North Shore campus (Appendix D). Individuals who were interested in participating in the study were contacted by phone or by email to outline the requirements of the study and the possible risks involved. Eligible volunteers were sent a copy of the participant information sheet to read prior to testing (Appendix E). All participants who met the requirements of the study were invited to attend the HRRI where the test procedure was explained in more detail. All participants were given several opportunities to ask questions. If the participants agreed to the test procedure, a consent form was completed (Appendix F) and an individual identification number allocated to each participant to conceal identity.

Using a random group allocation formula in a Microsoft Excel spreadsheet participants were randomly allocated into two groups: 1) biofeedback (BF) group who received feedback about their LS posture when lifting (n=18); and 2) non-biofeedback (NBF) group who received no feedback about their lifting posture (n=18). One of the authors (YN) enrolled participants and assigned them to the BF and NBF groups. Participants were blinded to their group allocation. The demographic characteristics of the participants can be found in Table 4.1.

Table 4.1 Mean (standard deviation) demographics for the two groups.

	BF (n = 18)	**NBF (n = 18)**
Age (years)	25.7(4.6)	25.6 (5.05)
Height (m)	1.80 (0.08)	1.84 (0.08)
Body weight (kg)	79.8 (11.2)	85.5 (13.84)
Body Mass Index (BMI)	24.7 (3.10)	25.6 (2.8)

BF, biofeedback group; BMI, body mass index; kg, kilograms;
m, meters; NBF, non-biofeedback group.

4.3 Experimental Measures

This study involved the collection of 3D kinematic and kinetic data, the measurement of LS posture and the provision of real-time postural biofeedback. The following section will outline the methods used.

4.3.1 Kinematic and Kinetic Data

4.3.1.1 Motion Analysis

Kinematic data of the trunk, pelvis and lower limbs were recorded using an Oqus nine camera motion analysis system (Qualysis AB, Gothenburg, Sweden) sampling at 120Hz. Seventy-seven lightweight (19 mm diameter), retro-reflective makers were attached to the skin of the participants to track the position and movement of body segments (Figure 4.1). Each of the nine individual cameras were placed to allow maximal visual coverage of the experimental setup. The relative 3D position of each marker (x, y, and z coordinates) was captured and stored using Qualysis Track Manager (QTM) version 2.15 software (Qualysis AB, Gothenburg, Sweden). The trajectories of each marker were tracked in QTM and gap filled according to a polynomial algorithm. Each lifting cycle (i.e. from when the box left the platform until it came to rest in the upright standing position) was saved in QTM and exported in C3D format for post - processing in Visual 3D, Version 5 (C-Motion Inc., Germantown, USA) software package.

4.3.1.2 Marker Placement

Markers were fixed to anatomical landmarks (Table 4.2) with double-sided tape and secured with hypoallergenic stretchable tape (Fixamull™) by an experienced physiotherapist (YN). Groups or 'cluster' markers defined the dimension and axis of each individual body segment (Cappozzo, Cappello, Croce, & Pensalfini, 1997), and were used to track each segment (Boocock et al., 2015). Three markers were attached to the box (Figure 4.1 and Table 4.2) to track its movement. A preliminary recording of each participant in a standing position was used as a reference posture ('static' trial) for biomechanical modelling. The set of markers used to define segments are detailed in Table 4.2. Medial markers (e.g. ankle and knees) were subsequently removed during the lifting task to avoid influencing the participant's lifting technique.

Table 4.2 Anatomical location of retro-reflective markers and body segments.

Marker location	Type	Body segment or equipment
Dynamic markers		
Right temple	B	Head
Left temple	B	
Front of head	B	
Top of head	B	
Acromion process	B	Trunk
T1 spinous process	B	
T3 spinous process	B	
Sternal notch	B	
Anterior arm	T	Upper arm
Posterior arm	T	
Proximal arm	T	
Distal arm	T	
Anterior lower arm	T	Lower arm
Posterior lower arm	T	
Proximal lower arm	T	
Distal lower arm	T	
Lateral wrist	B	Hand
Medial wrist	B	
Hand	B	
L1 – L2	B	Lumbosacral Spine
S1 – S2	B	
Anterior superior iliac spine	B	Pelvis
Posterior superior iliac spine	B	
Iliac crest	T	
Trochanter	B	Thigh
Anterior thigh	T	
Posterior thigh	T	
Proximal thigh	T	
Distal thigh	T	
Anterior leg	T	Leg

Posterior leg	T	Leg
Proximal leg	T	
Distal leg	T	
Heel (same heigh from floor as lateral foot)	B	Foot
Lateral foot (5th metatarsal head)	B	
Medial foot (1st metatarsal head)	T	
Box 1 (top right corner)	E	Equipment
Box2 (bottom left corner)	E	
Box 3 (top left corner)	E	
Static Markers		
Lateral elbow	B/T	Elbow joint
Medial elbow	B	
Lateral knee condyle	B/T	Knee joint
Medial knee condyle	B	
Lateral malleolus	B/T	Ankle joint
Medial malleolus	B	

Abbreviations: B, body marker; E, equipment marker; T, tracking marker;

4.3.1.3 Kinetic Data

Ground reaction forces and moments acting beneath each foot when performing the lifting task were measured using two floor mounted force plates (Advanced Medical Technology Inc., Watertown USA) (Figure 4.2). Ground reaction data were sampled at a rate of 1200Hz. Kinematic and kinetic data were synchronised and recorded for two lifting cycles.

4.3.1.4 Axes Orientation

The global movement coordinate system was defined by coordinates in the three orthogonal axes within QTM:

- The anterior-posterior axis (Y) was towards the midline of the two force plates.
- The medial-lateral axis (X) was perpendicular to the direction the participant was facing.
- The vertical axis (Z) was upwards.

The force plate axes (Figure 4.3) were aligned to match the global movement coordinates in QTM.

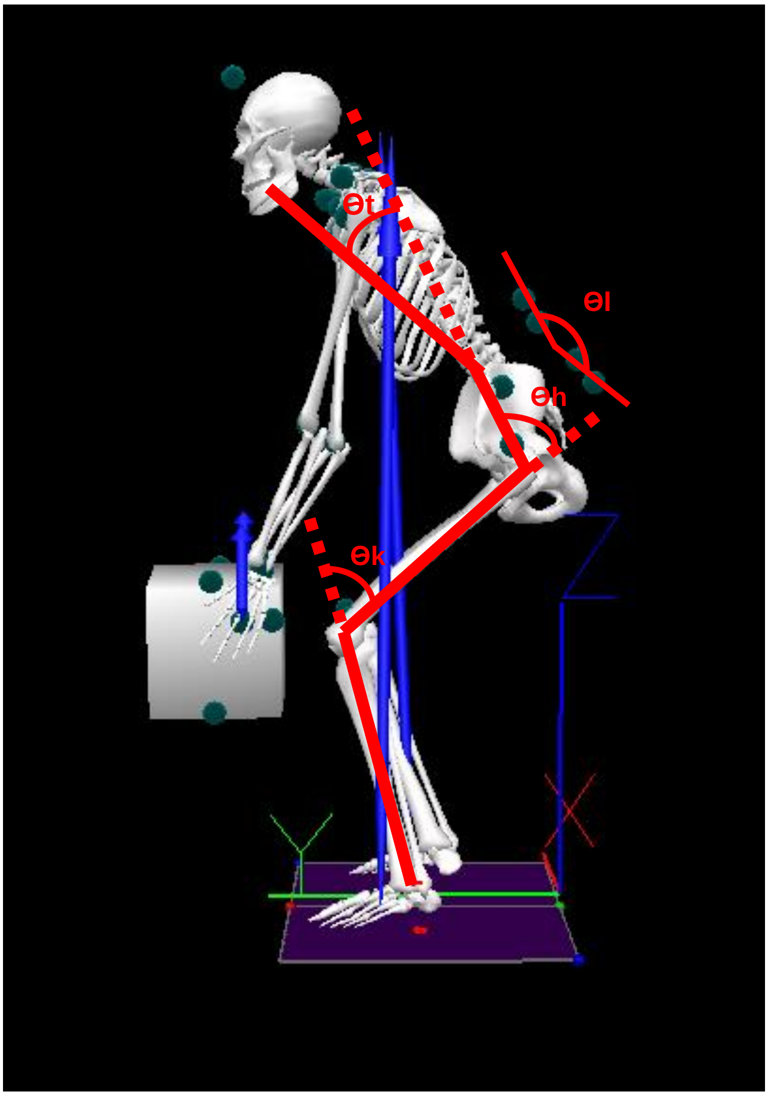

Figure 4.2 Fifteen segment, rigid-link dynamic biomechanical model of the right and left lower limbs (foot, shank and thigh), pelvis and trunk and upper limbs (arm, forearm, hand) with relative joint angles: ϴl = lumbosacral angle; ϴt = trunk angle; ϴh = hip angle; ϴk = knee angle. Blue arrows indicate the ground reaction forces acting at the feet and hands.

The joint coordinate system for the feet, knees, hips, pelvis, elbows, wrists, trunk, and neck were aligned to the recommendations of the International Society of Biomechanics Joint Coordinate Systems (Wu et al., 2002; Wu et al., 2005). The local coordinate axes were located at the proximal end of each segment, apart from the trunk, which was located at the distal end. The three orthogonal axes were defined in the same way as the global movement coordinate system.

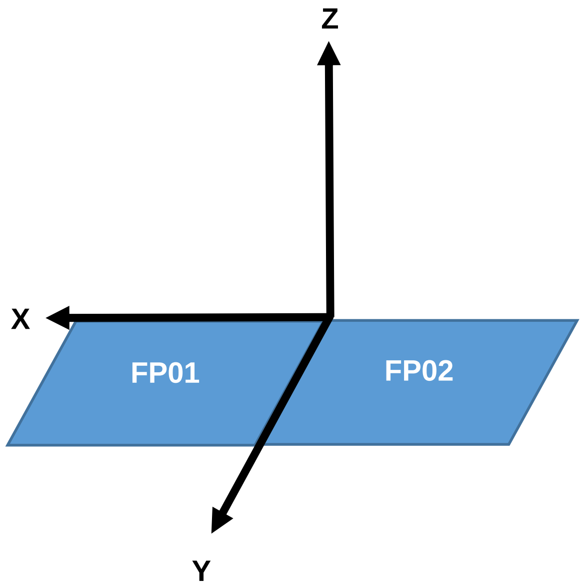

Figure 4.3 Laboratory force plate axis for force plate one (FP01) and force plate two (FP02)

4.3.1.5 Biomechanical Modeling

A 15 segment, rigid-link dynamic biomechanical model of the right and left lower and upper limbs (foot, shank, thigh, upper arm, forearm and hand), pelvis, trunk and head was constructed in Visual 3D (Version 5, C-Motion Inc., Germantown, USA) (Montgomery et al., 2011) (Figure 4.2). Body segments were represented as geometric objects (Hanavan, 1966) and scaled according to each person's anthropometrics (Boocock et al., 2015). The mass, centre of mass, and inertial characteristics of each segment were estimated using Dempster's regression equations (Dempster, 1955; Winter, 2009). Orthogonal axes for each body segment were aligned to the medial and lateral markers at the proximal and distal ends of each body segment, with the longitudinal axis passing through the segment endpoints (Boocock et al., 2015). Raw kinematic and kinetic data were smoothed using a recursive Butterworth lowpass filter set with a cut-off frequency of 6Hz and 12Hz, respectively. Relative joint angles and angular velocities were determined for the pelvis, hip, and knee joints (Figure 4.2). Inverse dynamics combined kinematic and kinetic data to estimate joint reaction forces and net moments about the pelvis, hips, and knees. Joint moments were normalised according to individual body weight.

4.3.1.6 Lumbosacral Angle

The Lumbosacral angle was measured using two approaches, one using 3D motion analysis, and the other using inertial sensors to provide real-time feedback (described later). The 3D motion analysis approach incorporates two pairs of markers. The LS angle was defined as the angle between the centre lines of the two pairs of reflective markers placed over the L1 and S1 vertebral spinous processes (Mawston et al., 2007), as illustrated in Figure 4.1. The L1 and S1 vertebral spinous processes were referenced from locating the intervertebral space between L4 and L5, at the same vertical level as the iliac crest in standing, and cross checked by palpating up from S2 spinous process level which is located at the same vertical level as the PSISs (Snider, Snider, Degenhardt, Johnson, & Kribs, 2011).

Prior to and directly following the dynamic lifting task, participants were instructed to maximally flex their spine while in a standing position (Dolan, Earley, et al., 1994). Participants flexed as far as possible while adopting slight knee flexion. This allowed dynamic measures of trunk and LS angle to be expressed as a percentage of full flexion, as follows:

$$\%Flexion = (\theta t - \theta s) / (\theta m - \theta s)$$

where:

θt	dynamic angle during task
θs	angle during the upright standing ‘static trial’
θm	maximum flexion angle

4.3.1.7 Bending moment

The bending moment resisted by the passive structures of the lumbar spine (*I*) was calculated using Dolan, Mannion, et al. (1994):

$$I = 7.97 \times 10E\text{-}5 \times F^3 + 12.9$$

where:

F = %Flexion (as above)

4.3.2 Biofeedback

LS postural biofeedback was provided by two Shimmer inertial sensors (Shimmer Sensing, Dublin, Ireland) placed on the first lumbar (L1) spinous process and the sacral vertebra (S1) (Figure 4.4). Inertial sensors have been shown to give good validity and reliability when measuring LS angle (Charry, Umer, & Taylor, 2011; Ha, Saber-Sheikh, Moore, & Jones, 2013; R. Y. Lee, Laprade, & Fung, 2003). Fixomull™ tape was applied over the sensors to minimize movement.

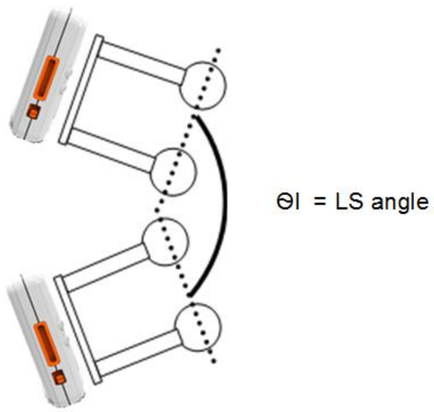

Figure 4.4 The lumbosacral (LS) angle defined as the angle between the centre lines of the two pairs of reflective markers attached to two Shimmer inertial sensors.

The inertial sensors continuously measured LSF and communicated via Bluetooth™ with a customized software programme operating on LabVIEW™ (National Instruments, Austin, Texas, USA, 2017, version 13.0). The computer interface provided audial feedback (a high pitched tone) when participants exceeded 80% of their maximum LSF ROM, a posture beyond which loading of the passive structures of the spine have been shown to significantly increase (Dolan, Earley, et al., 1994; Dolan, Mannion, et al., 1994). This is considered to represent bandwidth feedback, where the user receives feedback on correct and incorrect actions within set bandwidths (Lai & Shea, 1999). A real-time graphical user interface (GUI) enabled audial feedback to be switched on and off, and start and stop data capture.

4.3.3 Rating of Perceived Exertion

Participants were required to report on their perceived level of physical exertion by means of the rating of perceived exertion (RPE) scale (Figure 4.5) (Borg, 1990) immediately prior to and during the lifting task. This psychophysiological scale has been shown to be a valid and reliable measure of physical exertion (Borg & Kaijser, 2006). A written record was made of the participant's RPE immediately prior to lifting and every minute throughout the lifting task (Appendix G).

6	No exertion at all
7	
8	Extremely light
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Figure 4.5 Rating of perceived exertion (RPE) scale adapted from Borg and Kaijser (2006)

4.4 Experimental Procedures

4.4.1 Equipment Calibration

4.4.1.1 Motion Capture System

The motion capture system was calibrated at the start of each lifting session, according to the manufacturer's recommendations. This involved a calibration frame and 'wand' that defined the laboratory axes, and capture volume. The residual error of each of the nine motion capture camera was less than 0.7mm at every calibration. Force plates were also zeroed to offset electrical drift.

4.4.1.2 Shimmer Biofeedback Sensors

At the start of each lifting session the accelerometer, gyroscope and magnetometer of each Shimmer sensor was calibrated according to the manufacturer's recommendations. The software used the combined output of the two Shimmer sensors to monitor posture and provide biofeedback to the lifting participant. The sensors measured the relative LS angle of the participant during the lifting task by comparing the relative position and movement of each sensor.

4.4.2 Participant Preparation and Training

Following completion of the consent form each participant's height and weight were recorded along with their date of birth. They were asked to change into sports shorts and to remove their shirts in order for the retroreflective markers and shimmer sensors to be applied to their skin.

Each participant was asked to stand upright to obtain their 'static' trial in the 3D motion capture system and the Shimmer sensor systems. Each participant was then asked to maximally flex their spine forward while keeping their knees slightly bent. At this point a second recording was made that represented 100%LSF.

Participants were asked to stand with one foot on each force plate and as close as possible to the box to be lifted (Figure 4.1) located directly in front of the plates as described in section 4.3.2. They were given the opportunity to practice lifting and lowering the box until they felt comfortable with the equipment and technique. The weight in the box was not altered for the familiarization trials. The BF group performed the practice lift first without biofeedback and then with biofeedback turned on. While the biofeedback was turned on, the BF group were instructed to flex their spines in order to familiarize themselves with the biofeedback sound. Those in the NBF group only performed practice lifts without biofeedback. The participants in the BF group were told to adjust their own posture so they did not receive any biofeedback during the lifting task. Participants were not instructed about any lifting technique to adopt.

4.4.3 Testing Session

Following the practice lifts, the participants were asked to assume the same foot position. They were given a warning that lifting was about to commence and that the biofeedback would be turned on (for the BF group only). Once the participants commenced lifting (as described in Section 4.2.2) a kinematic and kinetic data file was created of the last two lifts of every minute of lifting. RPE was recorded every minute directly following the capture of the data file in order to minimize the effect of verbal communication on the kinematics and kinetics of the lifting activity. Throughout the lifting session participants in the BF group received an audial tone each time their spine exceeded 80% of maximal LS flexion. The NBF group received no biofeedback or postural advice throughout the lifting protocol.

4.5 Statistical Analysis

Data was initially checked for normality and descriptive analysis was performed. The dependent variables included peak angular displacement, peak angular velocity and peak joint moment during the lifting phase for the trunk, back, hip and knee. The mean value of two lifts every minute were calculated. Peak angular values for lumbar and thoracic ROM were also expressed as a percentage of total ROM. Other dependent variables included back, hip and knee moments normalized to body weight, RPE, and the number and times biofeedback was provided to participants in the biofeedback group.

As repeated measures on a participant are correlated, each kinematic and kinetic outcome measure was analysed using mixed models. Every model included two random effects: an intercept and a slope per participant. Fixed-effect terms were used to estimate differences between the two groups for intercept, slope and curvature, by introducing each additional term one at a time. Significance was determined by comparing pairs of sequential models (one with and one without the additional fixed effect term) using likelihood-ratio Chi-squared tests. The models were fitted using R version 3.3.3 (RCoreTeam, 2017) and the 'lme4' package (Bates, Mächler, Bolker, & Walker, 2014). Independent samples t-tests were used to investigate differences in the kinematic and kinetic variables for the two groups at the end of the lifting tasks. T-tests were undertaken using IBM SPSS Statistics version 24 (SPSS Inc., Chicago, USA). A statistical significance of 0.05 was applied throughout. The differences in intercepts between the two groups provided an indication as to whether the groups were different at the start of the lift, while the slopes or curvature provided an indication as to differences over time.

Sample size estimates were calculated using the G*Power version 3 (Faul, Erdfelder, Lang, & Buchner, 2007) with an effect size of 0.9, an alpha level of 0.05 and power of 0.8, the sample size was estimated to be 16 per group. Effect size was derived from a previous study (Boocock et al., 2015) where the mean group difference was 16.9% (group 1: mean 98.5%, standard deviation [SD] 15.2%; group 2: mean 81.6%, SD 23.3%).

4.6 Results

4.6.1 Overview

In this section the findings of the study will be presented, being divided into six sections. Firstly, the participant information will be presented and broken down into the group allocation of participants and their demographic characteristics. Secondly, the biofeedback results of the study will be presented. This is followed by the timing results. Kinematic and kinetic results will then be outlined with respect to the trunk, lumbar spine, hip and knee joints. Finally, RPE will be presented.

4.6.2 Participant Characteristics

All participants in the NBF group (100%) and 15 (83%) from the BF group completed the entire 20-minute lifting task. Participants who failed to complete 20 minutes cited excessive discomfort in the lower back as their primary reason for discontinuing. One participant stopped the lifting task at 12 minutes and the other two participants stopped at 18 minutes of lifting.

4.6.2.1 Group Allocation of Participants

The group allocation of participants throughout each stage of data collection is presented in Figure 4.6. Forty participants were initially recruited and assessed for eligibility to the study. The main reason for exclusion from the study was back injury in the previous six months. Eighteen participants were allocated randomly to the BF and NBF groups. Due to technical problems with the 3D system and measuring devices where the inertial sensors failed to communicate to the computer software, data from two participants in the NBF group were excluded.

4.6.2.2 Demographic Data

Thirty four participants completed the study of which 18 were in the BF group and 16 were in the NBF group. The demographic data of the participants included in the study is presented in Table 4.1. There were no statistically significant differences between any of the demographic characteristics of the two groups in terms of age, height, or body weight.

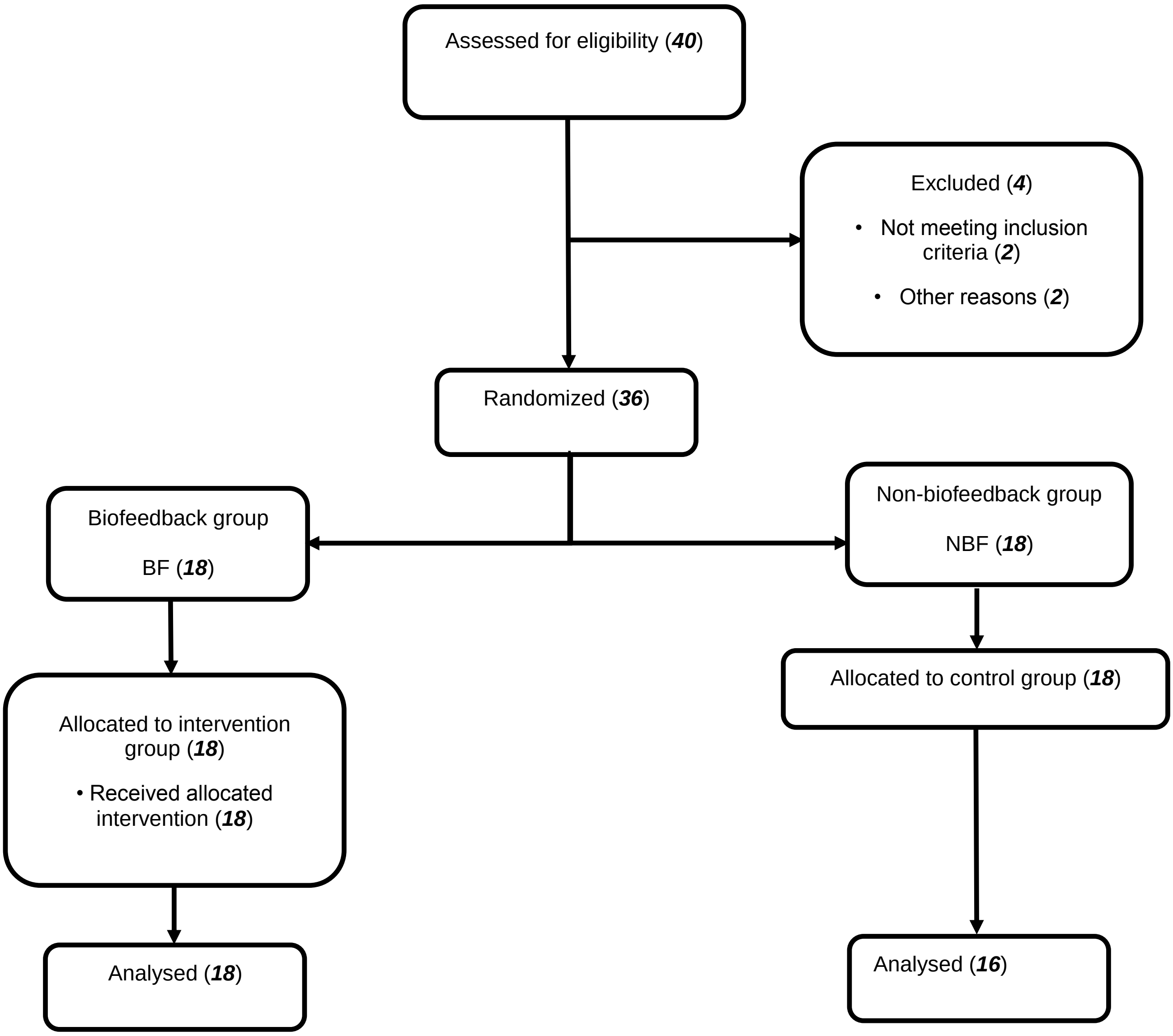

Figure 4.6. Participant groups throughout the study.

4.6.3 Biofeedback

The number of participants in the BF group who received biofeedback reached a maximum of 11 during the fifteenth minute of the lifting task (Figure 4.7) and reduced thereafter. The average time to the first instance of feedback was approximately seven minutes (95%CI = 4.508 - 9.642). The mean number of times feedback was received per participant, per minute, reached a maximum of 3.2 times during the eleventh minute (Figure 4.8). The mean number of times feedback was received steadily declined to approximately once per minute for the final three minutes of the 20 minute task.

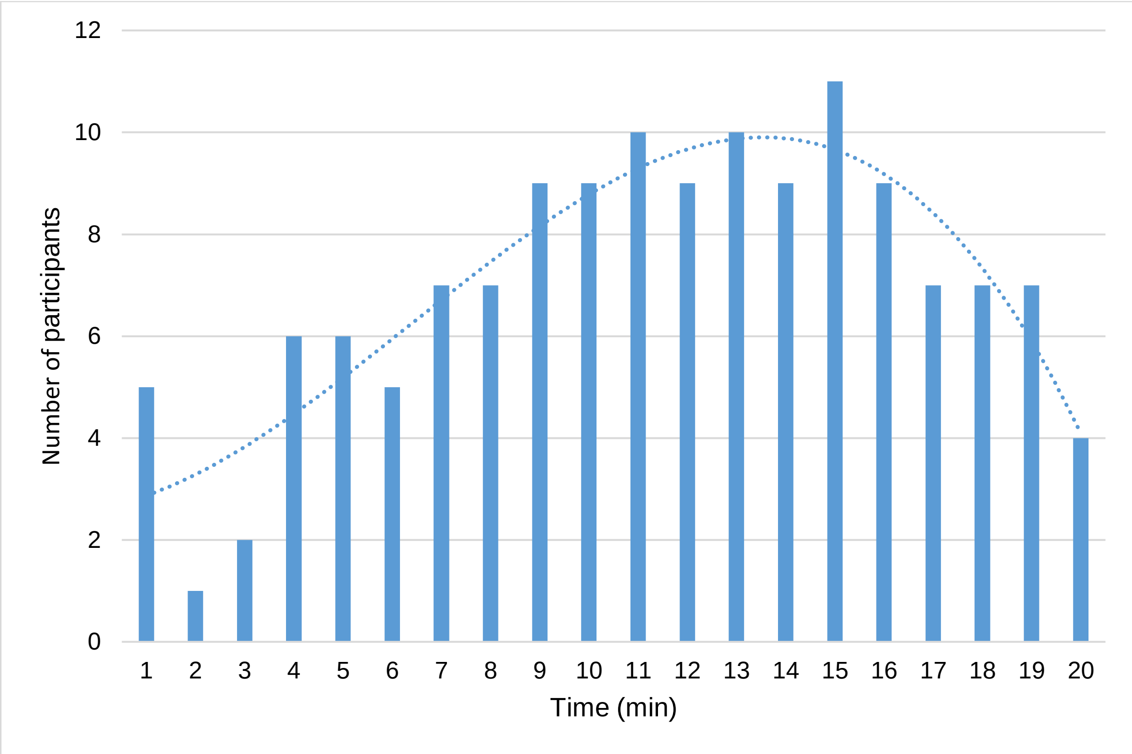

Figure 4.7. The number of participants in the BF group who received feedback throughout the lifting task.

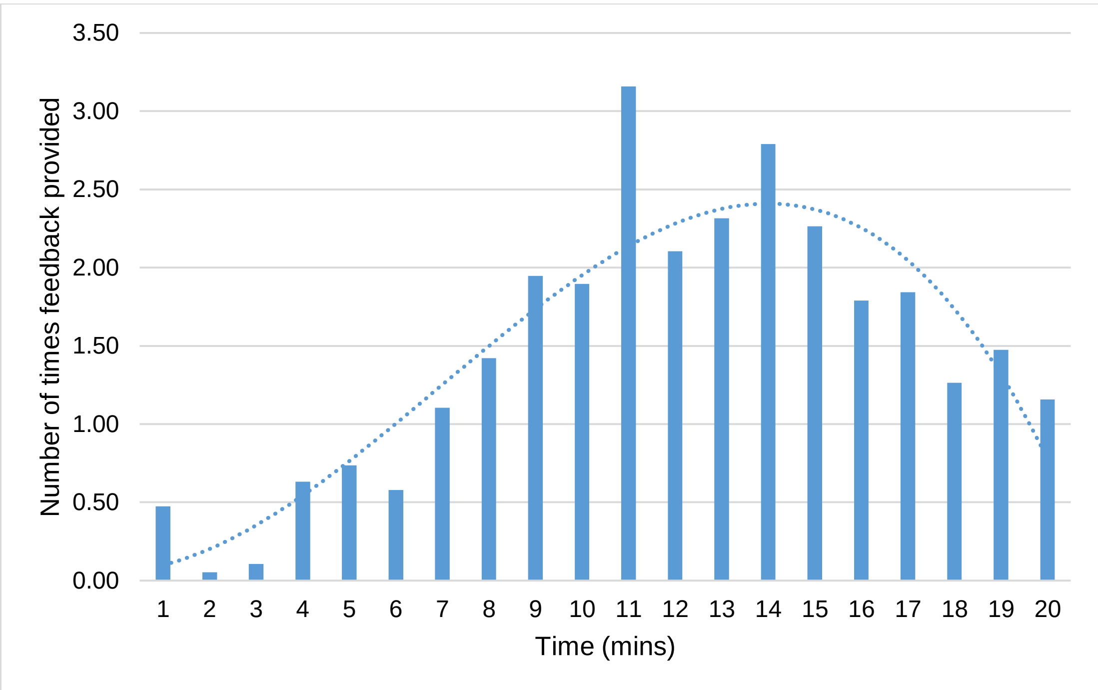

Figure 4.8. Mean number of times feedback was provided to participants in the BF group per minute throughout the lifting task.

4.6.4 Lifting Time

Although the lifting frequency was kept constant, the NBF group took significantly ($p < 0.001$) longer (mean = 1.56 s; 95% CI = 1.37 s–1.76 s) to perform a lift than the BF group (mean = 1.08 s; 95% CI = 1.01 s–1.14 s) at the start of the task. Although the mean lifting times reduced by the end of the lifting task, the NBF group still took significantly ($p = 0.01$) longer time to complete the lift (1.31 s; 95% CI = 1.17 s–1.45 s) when compared to the BF group (1.07 s; 95% CI = 0.99 s–1.14 s).

4.6.5 Kinematic Results

Linear and non-linear (quadratic) models were fitted to the kinematic data. The linear models provided the best fit for the kinematic data. Therefore, only linear models will be used in the following kinematic analysis presented. Table 4.3 presents a summary of all kinematic variables including mean values, 95% CI values, and P values at the start (1st minute) and end (20th minute) of the lifting task.

4.6.5.1 Lumbosacral Kinematics

There was a significant difference ($p < 0.001$) in peak percentage lumbosacral flexion (%LSF) between groups (BF versus NBF) at the start and end of the lifting task (Figure 4.9). There was also a significant difference in the slope of %LSF between groups ($p = 0.005$). The NBF group began the lifting task with significantly greater peak LSF compared to the BF group, and increased LSF at a greater rate (Figure 4.9). At the end of the lifting task the NBF group reached near-maximal LSF (mean of 97.9%), whereas, the BF group had an average peak LSF of 64.3% in the last minute of the lifting task (Table 4.3). There was a mean increase in %LSF from the beginning to the end of the lifting task of 29.2% and 18.7% for the NBF and BF groups, respectively (Figure 4.9).

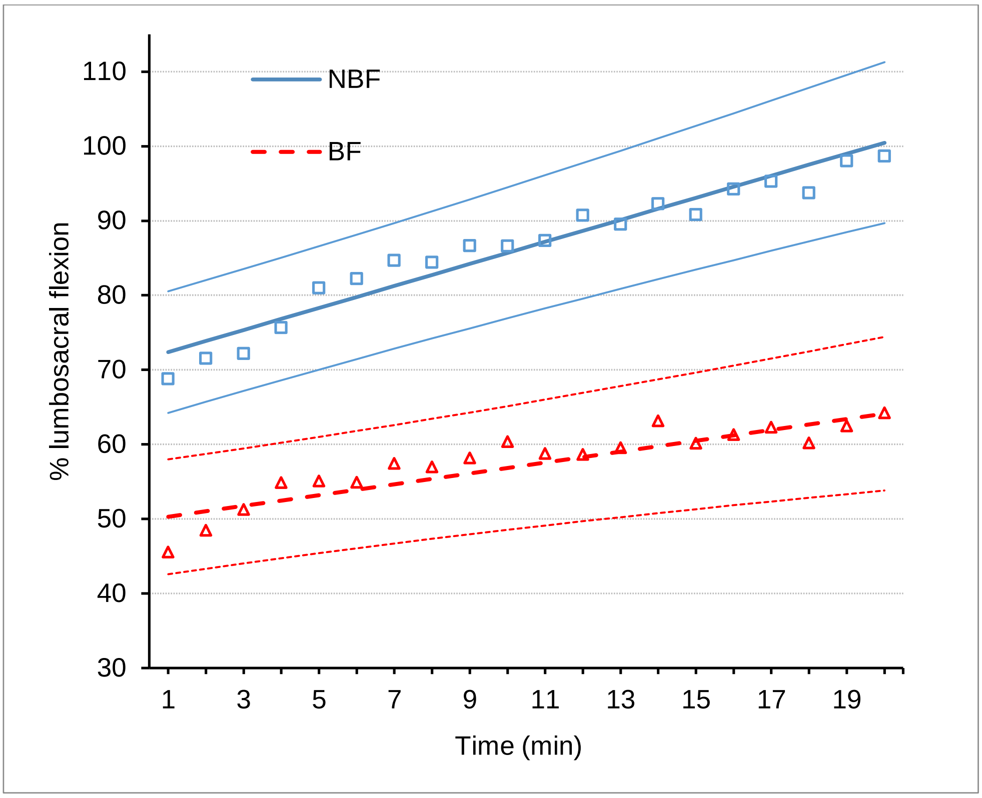

Figure 4.9. Peak percentage of lumbosacral flexion (%LSF) for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted linear models and corresponding 95% confidence intervals over the lifting task.

Table 4.3 Kinematic variables.

	Start (1st min)					End (20th min)				
	BF		NBF		P Value*	BF		NBF		P Value^
	Mean	95% CI	Mean	95% CI		Mean	95% CI	Mean	95% CI	
LSF angle (deg)	176.3	175.5-177.0	188.4	182.7-194.0	=0.005	186.5	186.0-187.1	201.4	196.9-205.8	< 0.001
%LSF	45.6	42.0-49.2	68.7	57.4–80.0	< 0.001	64.3	58.7- 69.9	97.9	90.9-104.8	< 0.001
LSF angular velocity (°/s)	35.4	33.5-37.3	28.2	19.8–36.5	NS (0.052)	49.3	46.3–52.4	56.8	47.3–66.3	NS (0.301)
TF angle (deg)	22.8	22.2-23.4	20.3	14.8-25.8	NS (0.771)	26.3	25.5-27.1	33.2	27.6-38.8	< 0.001
%TF	41.4	35.8–47	61.1	50–72.2	< 0.001	47.3	43.2-51.4	85.4	77-93.8	< 0.001
TF angular velocity (°/s)	29.4	27.8-30.9	36.8	26.3-47.2	NS (0.25)	47.5	38.9-56.2	69.0	57.3-80.8	< 0.001
Hip angle	87.5	87.1- 87.9	93.0	87.1- 98.9	NS (0.180)	86.3	85.8- 86.8	87.5	81.8- 93.1	NS (0.768)
Hip angular velocity (°/s)	137.4	134.7-140.0	85.3	71.9-98.7	< 0.001	141.9	139.7-144.0	93.3	82.5-104.0	< 0.001
Knee angle	67.5	56.2-78.8	63.2	52.1-74.2	NS (0.668)	64.2	57.3-71.1	53.2	43.8-62.6	=0.009
Knee angular velocity (°/s)	102.5	99.3-105.6	75.3	59.4-91.2	=0.008	113.1	110.0-116.3	83.4	66.5-100.4	=0.003

P value* denotes the intercept difference of fitted linear models; P value^ denotes the difference between groups based on independent t-tests at 20 minutes.

There was a significant difference in LSF angle between groups at the start and end of the lifting task (Figure 4.10). There was a mean increase in peak lumbar angle from the beginning to the end of the lifting task of 13° and 10.2° for the NBF and BF groups, respectively (Figure 4.10). The NBF group progressively increased flexion whereas the BF group did not.

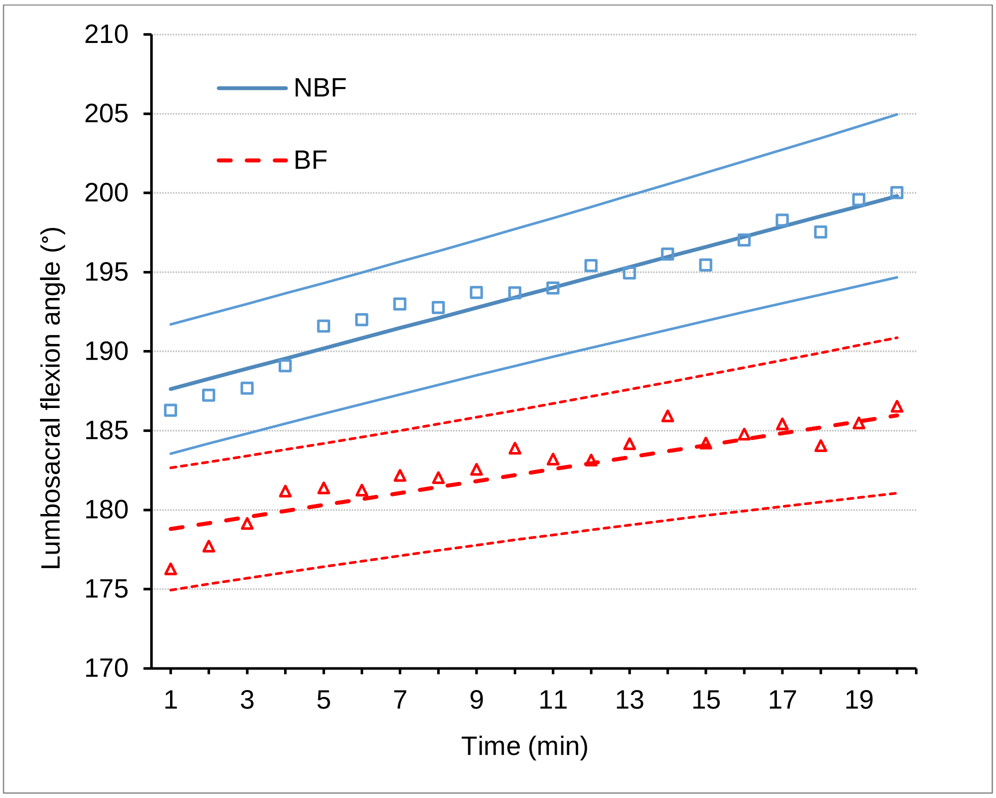

Figure 4.10. Peak lumbosacral flexion (LSF) angle (°) for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted linear models and corresponding 95% confidence intervals over the lifting task.

Peak lumbar angular extension velocity at the beginning and end of the lifting task did not significantly differ between groups (Figure 4.11). However, significant differences were found between the linear slopes fitted to each group ($p = 0.008$), with the NBF increasing extension velocity at a greater rate than the BF group throughout the lifting task.

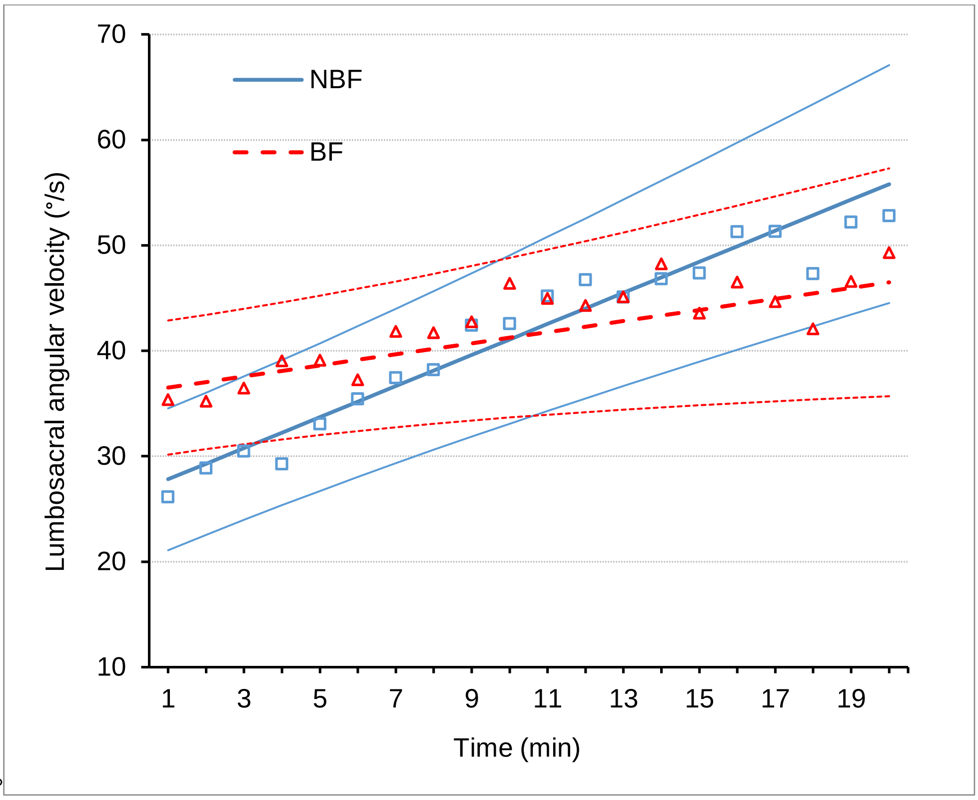

Figure 4.11. Peak lumbosacral extension angular velocity (°/s) for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted linear models and corresponding 95% confidence intervals over the lifting task.

4.6.5.2 Trunk Kinematics

Percentage peak trunk flexion (%TF) and peak trunk flexion (TF) followed a similar pattern to LS angle in both groups (Figure 4.12 and Figure 4.13 respectively). There were significant differences between groups at the start and end of the lifting task, with the BF group displaying significantly less %TF. By the end of the 20th minute, the NBF group participants flexed their trunk to 85.4% of their maximum range, compared to 47.3% in the BF group. This represented a mean increase in trunk angle from the beginning to the end of the lifting task of 24.3% (12.9°) and 5.9% (3.5°) for the NBF and BF groups, respectively. Significant differences were found between the linear slopes of the fitted models ($p = 0.007$) with the NBF group progressively increasing flexion at a greater rate compared to the BF group.

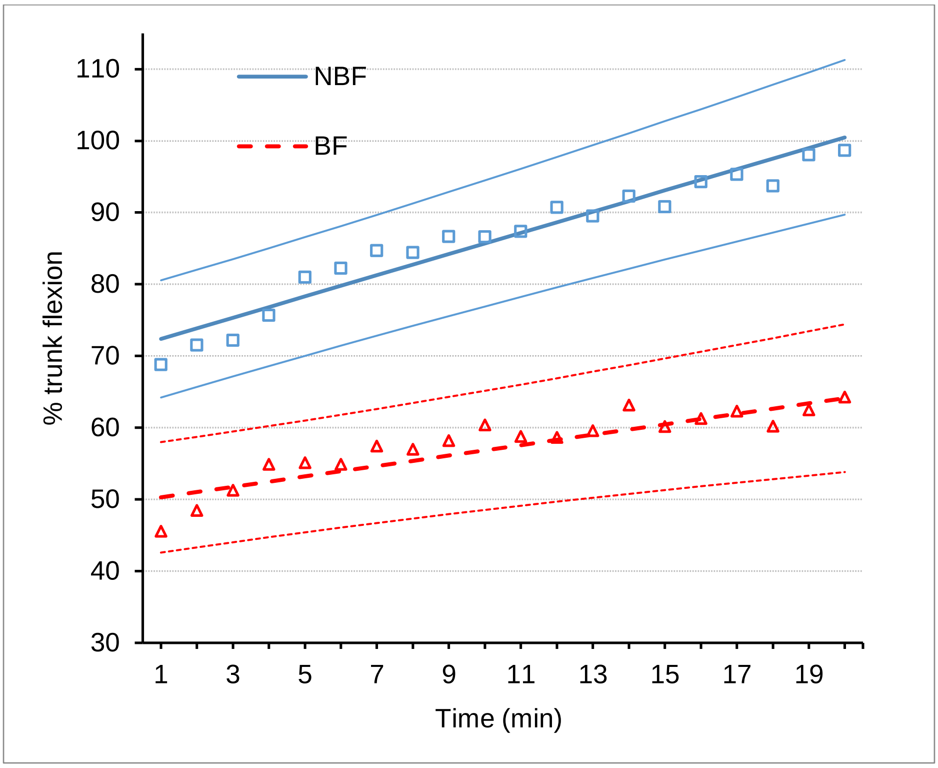

Figure 4.12. Peak percentage trunk flexion angle for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted linear models and corresponding 95% confidence intervals over the lifting task.

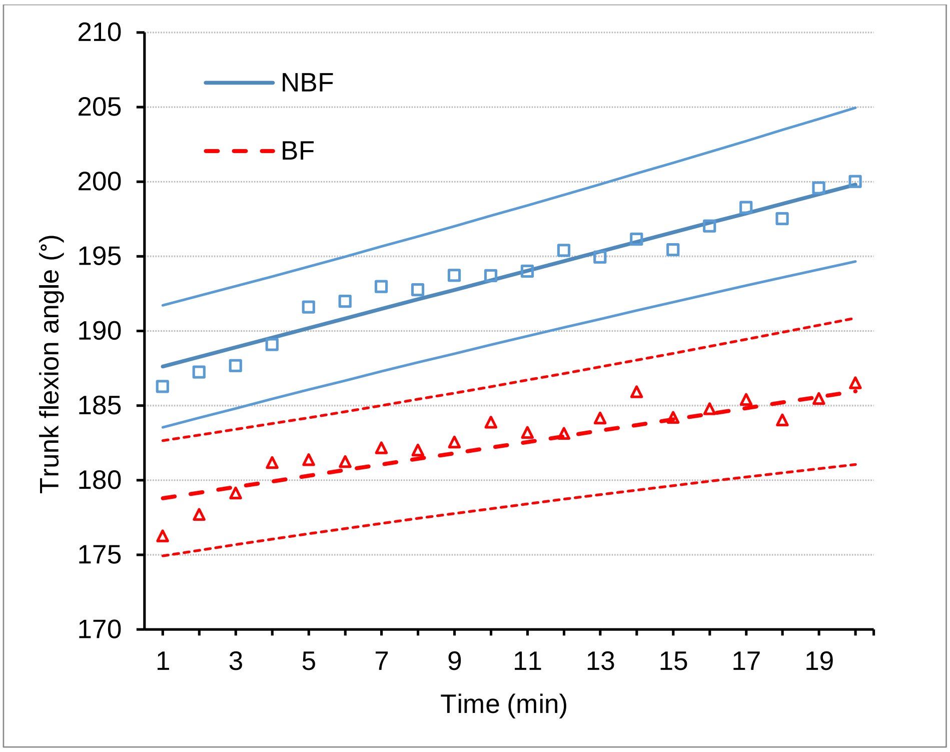

Figure 4.13. Peak trunk flexion angle (°) for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted linear models and corresponding 95% confidence intervals over the lifting task.

4.6.5.3 Lower Limb Kinematics

No difference was found between the right and left lower leg kinematics. Therefore, only the right peak hip and knee kinematics are presented. There were no significant differences in hip angle at the start or end of the lifting task (Figure 4.14). The NBF group did, however, reduce the mean peak hip flexion angle by 5.5° from the start to the end of the session, whereas the BF group only reduced the mean hip angle by 1.2° from start to end.

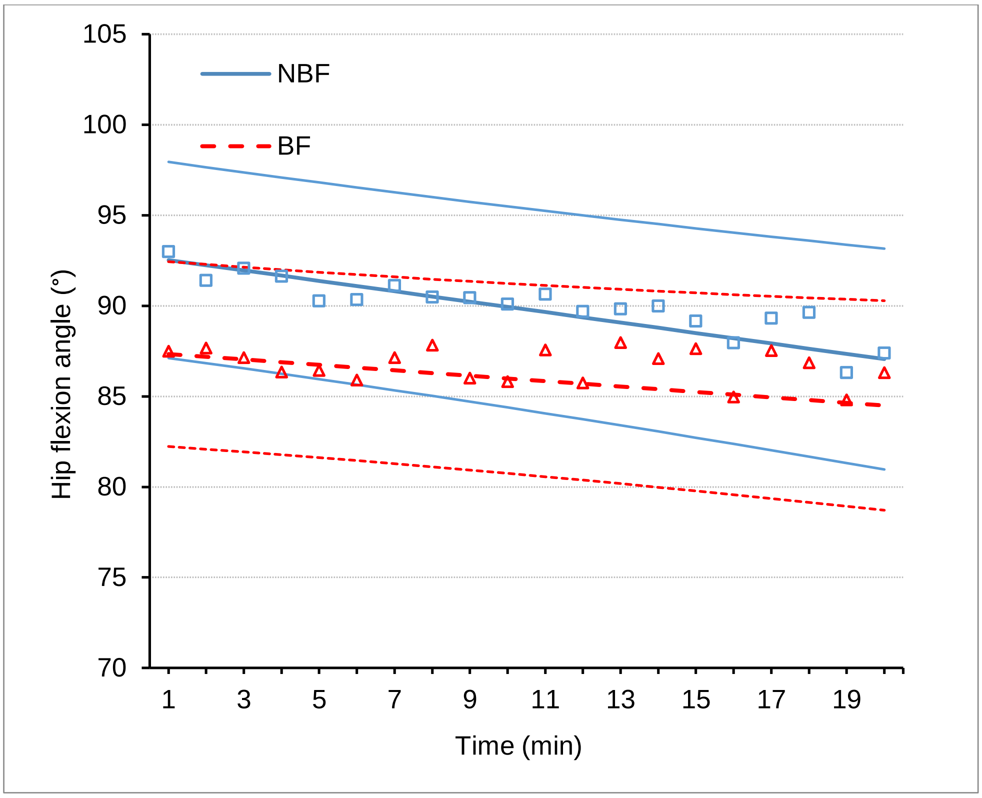

Figure 4.14. Peak hip flexion angle (°) for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted linear models and corresponding 95% confidence intervals over the lifting task.

There were significant differences in hip angular velocities at the start ($p < 0.001$) and the end ($p < 0.001$) of the lifting task between the two groups (Figure 4.15). Both groups increased their mean hip angular velocities from the start to the end of the lifting task.

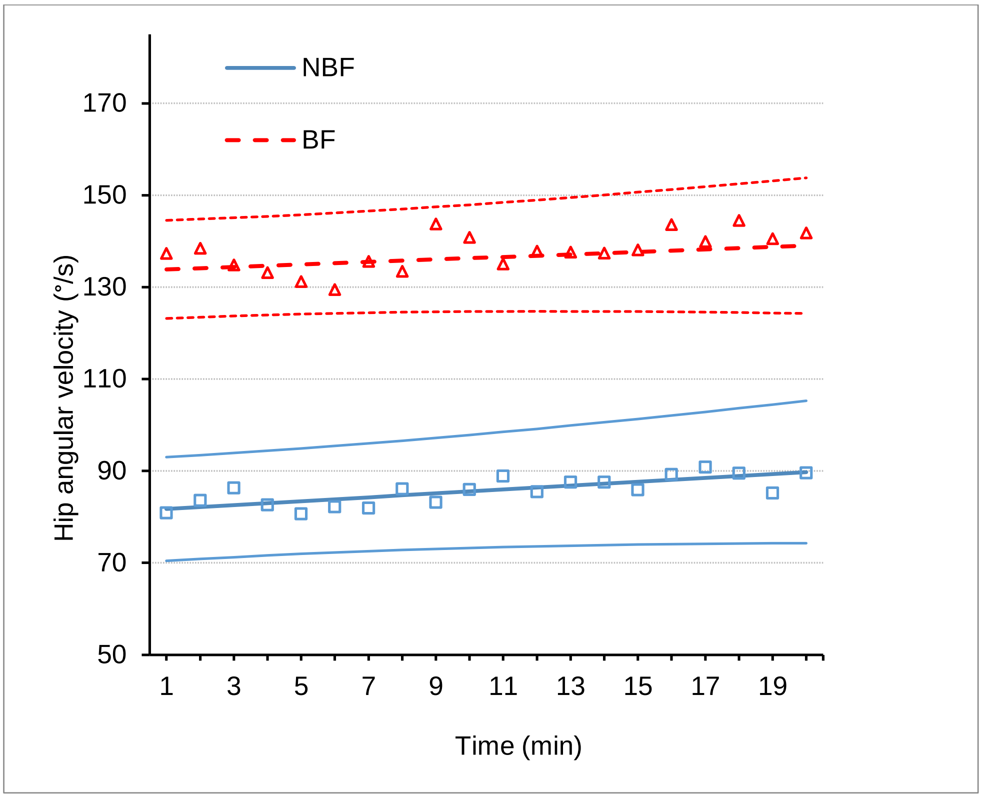

Figure 4.15. Peak hip extension angular velocity (°/s) for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted linear models and corresponding 95% confidence intervals over the lifting task.

There were no significant differences in knee flexion between the two groups at the start of the lifting task (Figure 4.16). However, at the end of the lifting task mean peak knee angles were significantly different ($p = 0.009$). The BF group maintained a similar knee flexion throughout the lifting task, whereas the NBF had decreased mean knee flexion by the end of the task. Significant differences were found between the linear slope models fitted to each group ($p = 0.025$), with the NBF decreasing knee flexion at a more rapid rate compared to the BF group.

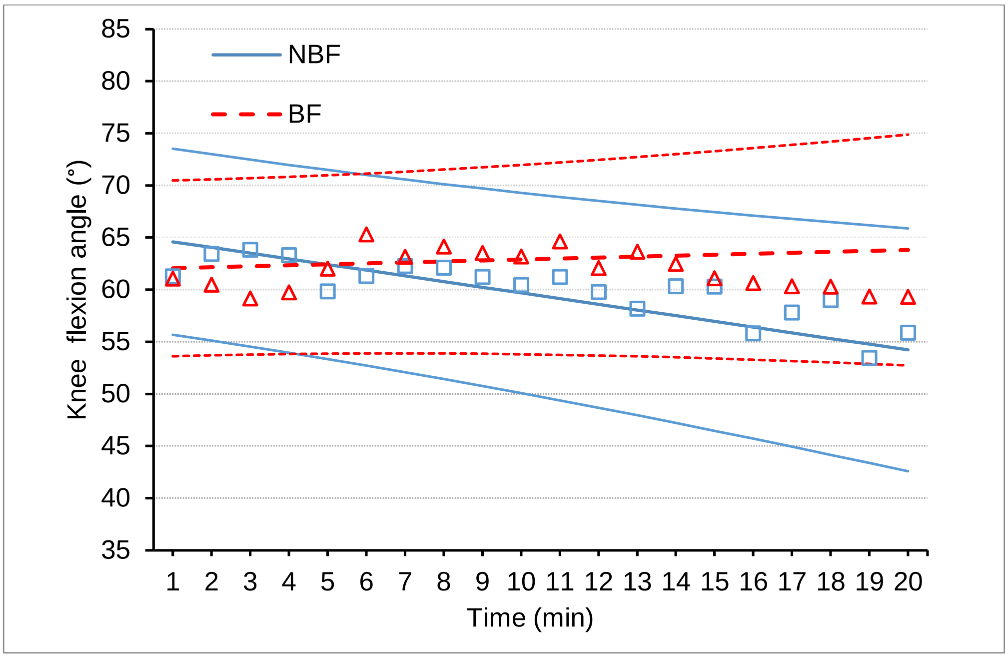

Figure 4.16. Peak knee flexion angle (°) for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted linear models and corresponding 95% confidence intervals over the lifting task.

During extension, peak knee angular velocities (Figure 4.17) were significantly higher in the BF group compared to the NBF group at the start ($p = 0.008$) and end ($p = 0.003$) of the lifting task. The difference between the linear slopes was non-significant ($p = 0.351$) between the two groups.

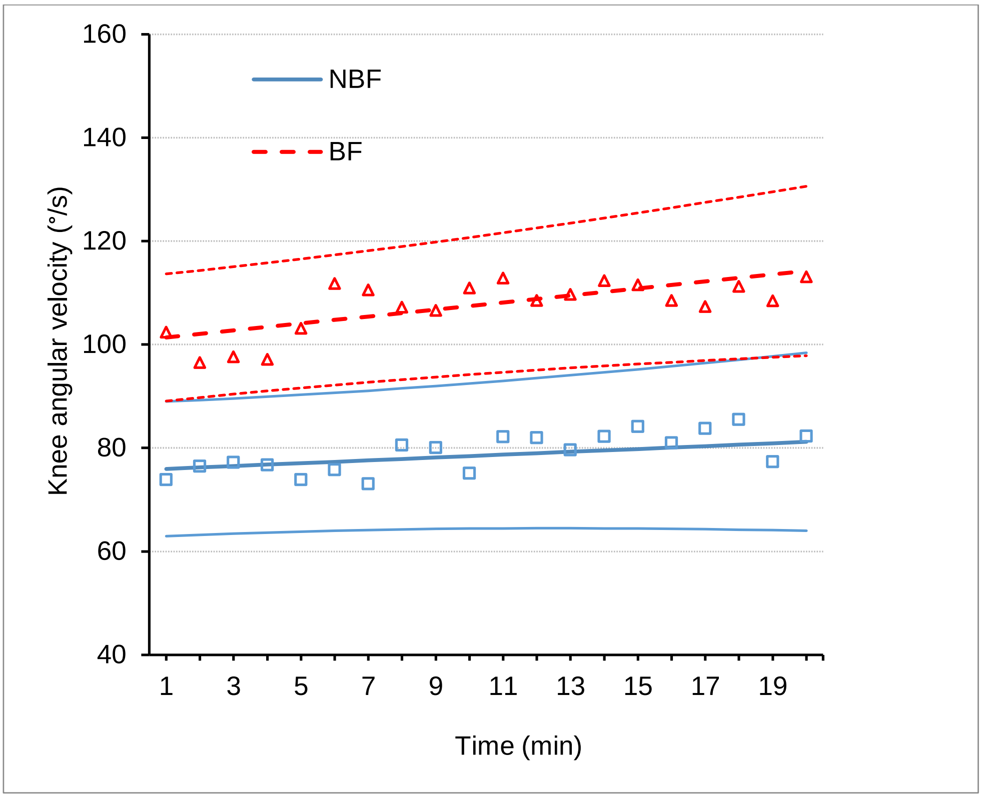

Figure 4.17. Peak knee extension angular velocity (°/s) for non-biofeedback (NBF) and biofeedback (BF) groups, with fitted linear models and corresponding 95% confidence intervals over the lifting task.

4.6.6 Kinetics

Subsequent to the fitting of linear and non-linear (quadratic) models, the quadratic models provided the best fit for the kinetic data. Therefore, only quadratic models will be used in the following kinetic analysis, with the exception of the passive back bending moment, which linear was most suitable. Table 4.4 presents a summary of all kinetic variables including mean values, 95% CI values, and P values at the start (1st minute) and end (20th minute) of the lifting task.

Table 4.4 Kinetic variables.

	Start (1st min)					End (20th min)				
	BF		NBF		p Value*	BF		NBF		p Value^
	Mean	95% CI	Mean	95% CI		Mean	95% CI	Mean	95% CI	
Peak L5/S1 moments (Nm/kg)	2.40	2.36-2.45	2.20	2.10-2.30	NS (0.177)	2.38	2.35-2.42	2.18	2.03-2.33	NS (0.953)
Peak passive bending moment (Nm/kg)	0.04		0.26		=0.002	0.15		0.74		< 0.001
Peak hip moments (Nm/kg)	1.34	1.21- 1.47	1.52	1.43- 1.62	NS (0.544)	1.20	1.09- 1.31	1.41	1.31- 1.50	NS (0.682)
Peak knee moments (Nm/kg)	0.46	0.44- 0.49	0.43	0.38- 0.49	NS (0.089)	0.40	0.37- 0.43	0.38	0.28- 0.48	NS (0.372)

p value* denotes the intercept difference of fitted quadratic models; p value^ denotes the difference between groups based on independent t-tests at 20 minutes.

4.6.6.1 Lumbosacral Kinetics

When lifting, there were no significant differences between normalised peak back bending moments (Figure 4.18) between the two groups. The BF group did, however, maintain a higher mean moment particularly at the start and end of the lifting task where the moment was approximately 9% higher compared to the NBF group.

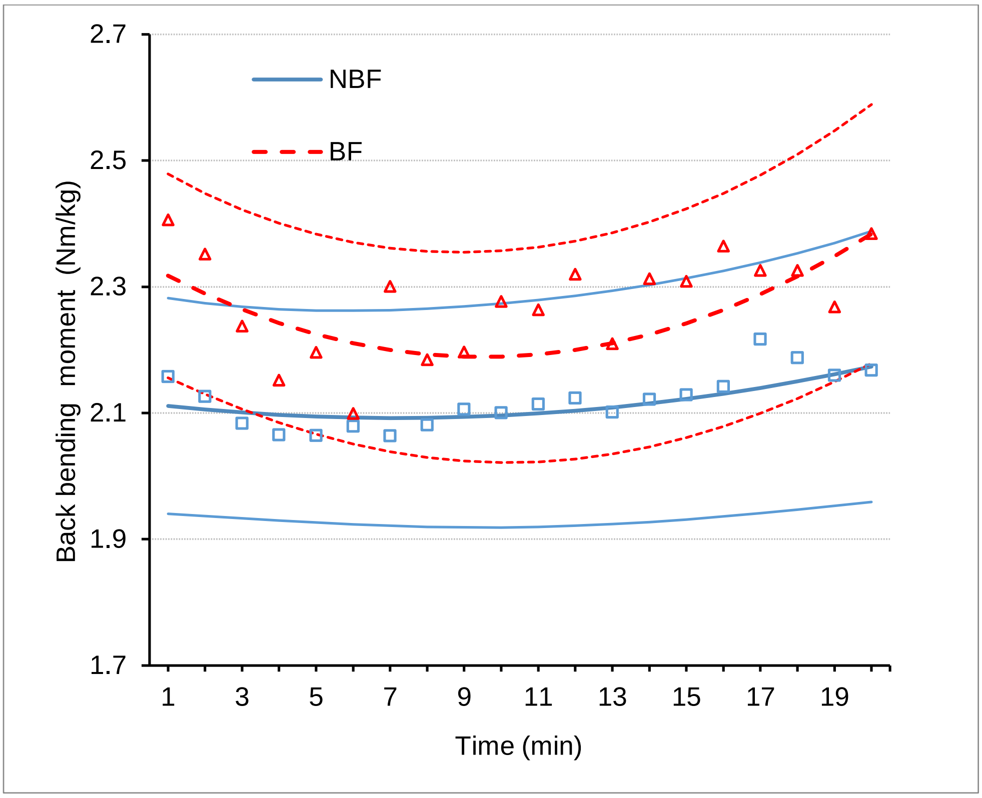

Figure 4.18. Mean peak back bending moments for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted quadratic models and corresponding 95% confidence intervals.

4.6.6.2 Bending Moments Resisted by Passive Structures of the Spine

The normalised bending moment resisted by the passive structures of the spine was significantly ($p < 0.001$) higher at the end of the lifting task in the NBF group (1.12Nm/kg) compared to the BF group (0.44Nm/kg) (Figure 4.19). The percentage of total bending moment resisted by passive structures was higher in the NBF group at the start of the lifting task (25.8%) compared to the BF group (12.5%). Both groups gradually increased the bending moment resisted by passive structures over 20 minutes, with the NBF group showing an increased rate of change (slope) ($p < 0.001$) relative to the BF group. At the end of 20 minutes the percentage of total bending moment (%Moment) resisted by the passive structures was 53.3% in the NBF group and 18.8% in the BF. This equated to an increase of 44.8Nm in bending moment resisted by passive structures at the end of 20 minutes in the NBF group (total bending moment = 91.6Nm) compared to a 12.4Nm increase in the BF group (total bending moment = 53.3Nm).

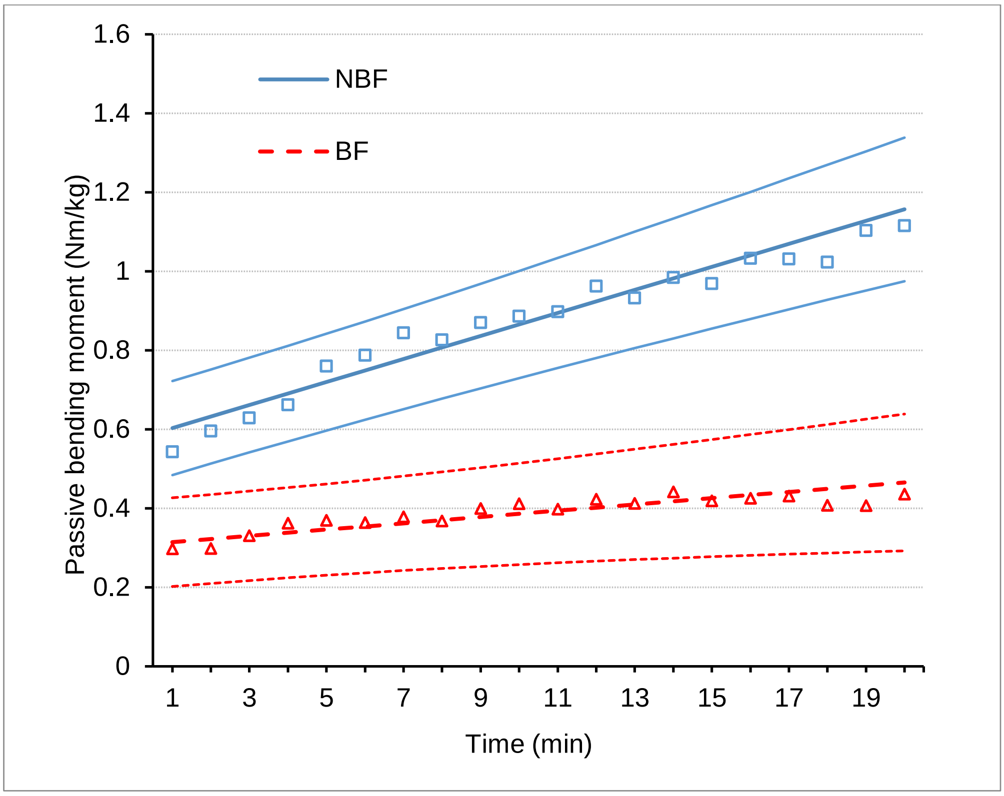

Figure 4.19. The normalised passive bending moment for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted linear models and corresponding 95% confidence intervals over the lifting task.

4.6.6.3 Lower Limb Kinetics

No difference was found between the right and left lower limb peak hip and knee moments. Therefore, only data for the right lower limbs are reported. No significant differences between the groups were found for peak hip extensor moments at the start or the end of the lifting task (Figure 4.20).

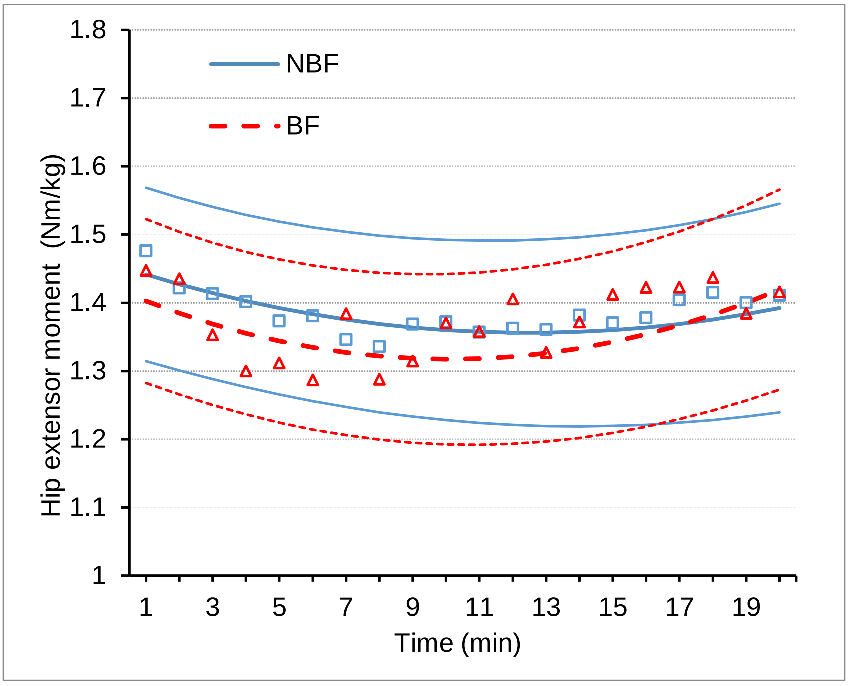

Figure 4.20. Mean peak hip extensor moments for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted quadratic models and corresponding 95% confidence intervals.

The peak knee extensor moment was higher throughout the task in the BF group though not significant (Figure 4.21).

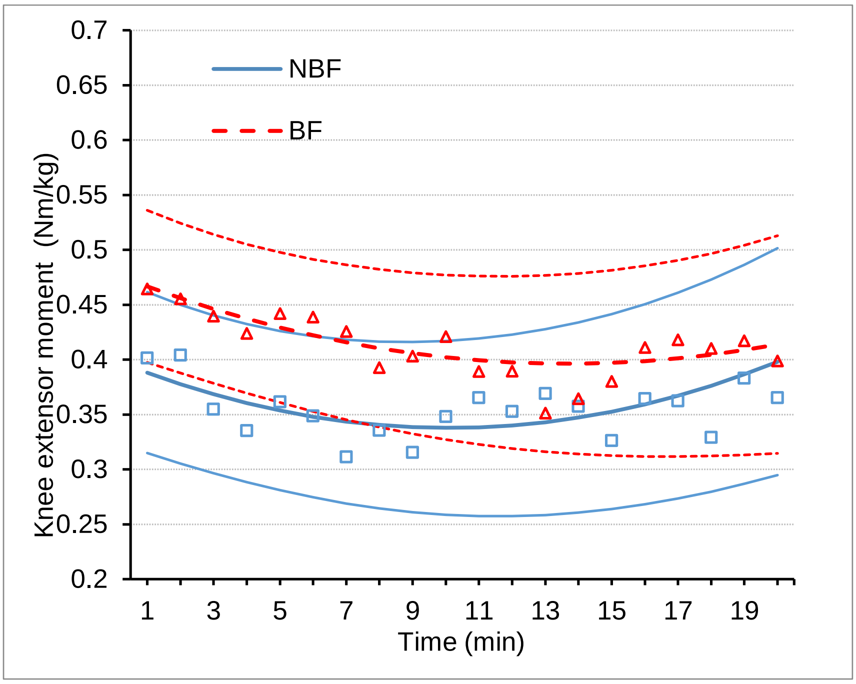

Figure 4.21. Mean peak knee extensor moments for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted quadratic models and corresponding 95% confidence intervals.

4.6.7 Rating of Perceived Exertion (RPE)

Subsequent to the fitting of linear and non-linear (quadratic) models, the quadratic models provided the best fit for the RPE data. Therefore, only quadratic models will be used in the following RPE analysis. The fitted quadratic models for RPE were significantly different between the two groups ($p < 0.001$). There were no significant differences in intercept values (the start of lifting), but the mean RPE for the NBF group was significantly higher when compared to the BF group at the end of the 20-minute lifting task ($p < 0.001$) (Figure 4.22). It was noted that three participants in the BF group presented as extreme outliers and, therefore, a sensitivity analysis was undertaken in which their data were excluded. After adjusting for outliers, there were no significant differences between the fitted quadratic models of the two groups ($p > 0.05$) (Figure 4.23). The most notable increase in RPE occurred during the first 10 minutes of lifting with the RPE plateauing during the last six minutes of lifting (Figure 4.23).

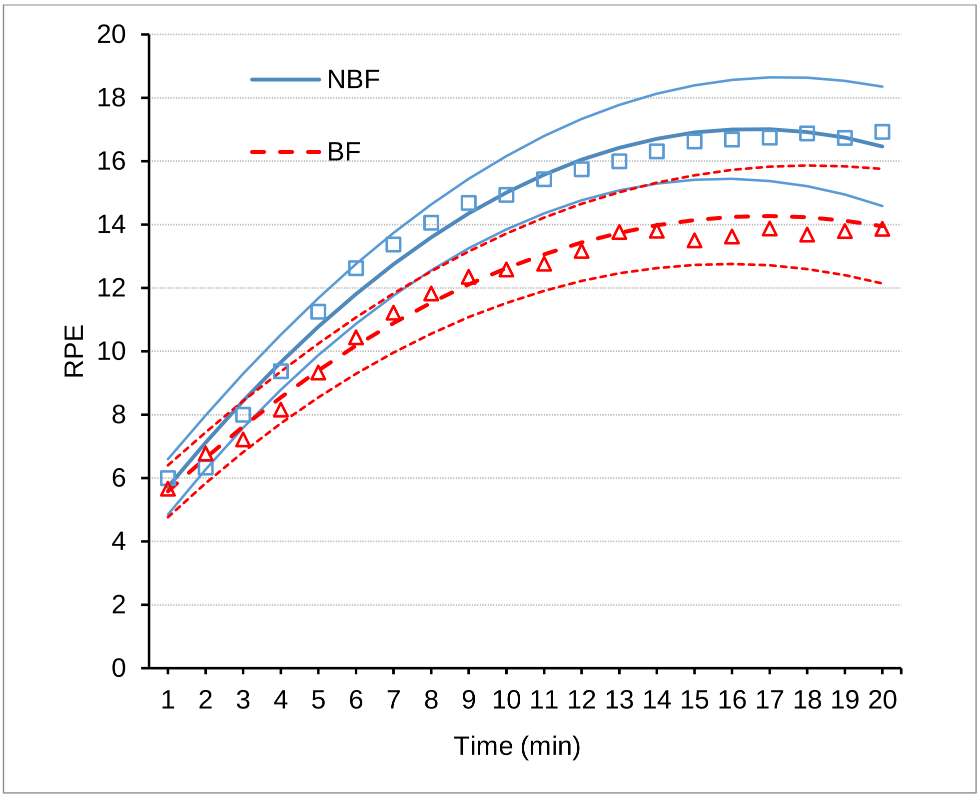

Figure 4.22. The mean rating of perceived exertion for the non-biofeedback (NBF) and biofeedback (BF) groups, with fitted quadratic models and corresponding 95% confidence intervals.

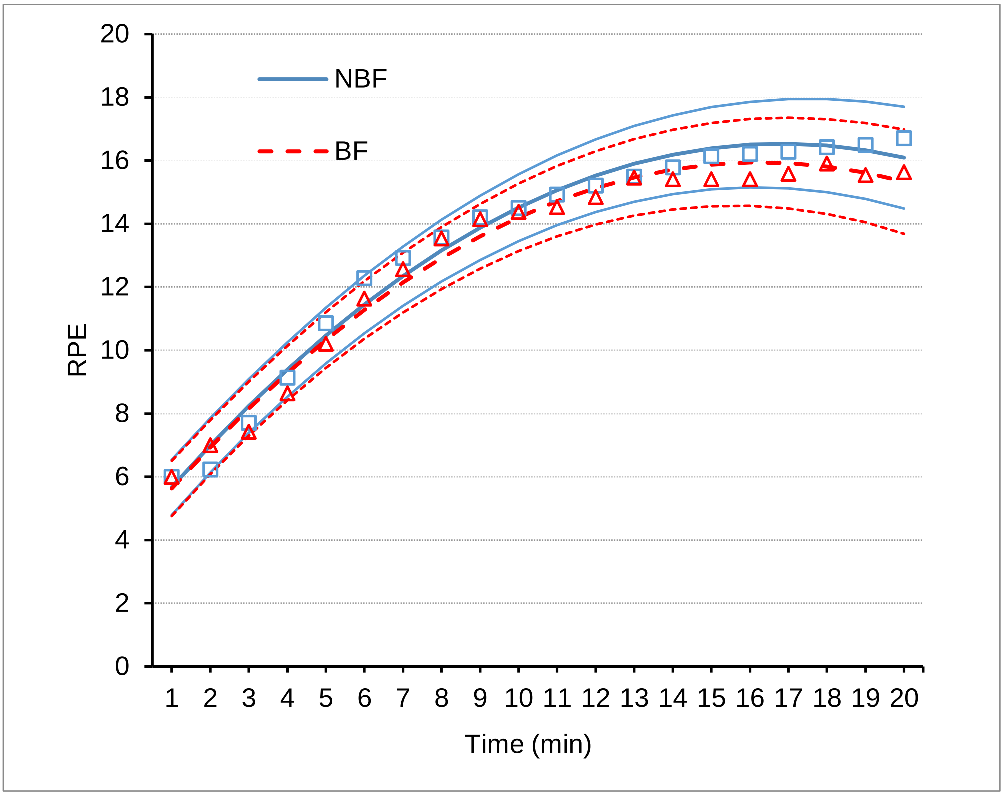

Figure 4.23. The mean rating of perceived exertion for the non-biofeedback (NBF) and biofeedback (BF) groups (with outliers removed), with fitted quadratic models and corresponding 95% confidence intervals.

4.7 Discussion

4.7.1 Influence of Biofeedback on Lumbosacral Posture

Biofeedback of LS posture resulted in decreased overall peak LSF throughout the lifting task, leading to a mean peak LSF that was below the prescribed threshold of 80% maximum at 20 minutes of repetitive lifting. In contrast, the NBF group showed a linear increase in LSF which reached near-maximum LSF at the end of 20 minutes.

Consequently, the null hypothesis (1) was rejected that there would be no difference in LSF during a repetitive lifting task as a result of biofeedback.

Other studies have found similar results, where repetitive lifting in the absence of feedback has led to increases in LSF over time in young, healthy individuals (Boocock et al., 2015; Dolan & Adams, 1998; Sparto et al., 1997). Boocock et al. (2015) found similar increases in LSF in a group of participants who were of a similar age to the current study and performed an identical lifting task. Measures of EMG muscle activity and a shift in median frequency of back muscle activity suggested to the authors that paraspinal muscles had become fatigued and there was likely to have been a shift from active (e.g. muscle) to passive load bearing structures in the spine (Dolan, Earley, et al., 1994; Howarth & Mastragostino, 2013).

In the present study, reduced LSF displayed by the BF group demonstrates that biofeedback was an effective modality to control LS posture throughout the repetitive lifting task. A previous systematic review concluded that biofeedback can be effective in physical rehabilitation in areas such as postural control, movement, and force regulation (Giggins et al., 2013). A number of studies have investigated the effect of real-time feedback on spinal posture (Breen et al., 2009; Çelenay et al., 2015; Dean & Dean, 2006; Lou et al., 2012; Magnusson et al., 2008; Ribeiro et al., 2014; Vignais et al., 2013; Wong & Wong, 2008) and found positive outcomes in altering spinal posture during functional activities (refer to Table 2.5 in Section 2.8.3). More research is required to further strengthen the argument for the use of real-time biofeedback in altering spinal posture.

4.7.2 The Learning Effect of Biofeedback

There was no indication that participants became reliant on biofeedback, as evidenced by the amount and frequency of biofeedback. The amount of feedback provided to BF participants reduced after 13 minutes, suggesting a learning effect. This was contrary to what might be expected, as it has been shown that %LSF, and a potential need for feedback, is likely to increase during repetitive manual handling (Boocock et al., 2015; Dolan & Adams, 1998; Sparto et al., 1997). The reduced reliance on feedback in the latter stages of lifting may be associated with motor learning and the closed-loop theory of motor learning which proposes that feedback from error detection (such as lumbar flexion beyond a designated angle) is fed back into the system to correct future attempts (Adams, 1987). Adams (1987) suggests that the greater the number of acquisition trials, the greater the subject's capability of estimating the accuracy of subsequent responses in a motor learning situation. Importantly, however, this motor skill acquisition does stabilize after sufficient trials and is task-specific (Adams, 1987). Within the current study, the optimum motor learning period appeared to be 13 minutes after which the motor skill had improved to a point where lifting posture could be maintained with reduced feedback.

The type of feedback (i.e. timing and frequency) can play an important role in the observed learning effect. Whilst LS posture was measured continuously throughout the lifting task, biofeedback was only provided when the participant exceeded 80% of maximal LSF. This type of biofeedback, using a target value is often referred to as bandwidth feedback. There is evidence to suggest that real-time bandwidth feedback can be effective in motor learning, particularly when the task is complex (Sigrist et al., 2013). Ribeiro et al. (2014) used a device attached to each subject's belt that gauged lumbopelvic movement by measuring forward and backward tilt as an indication of low back posture and found that the real-time, bandwidth feedback resulted in significant reductions in flexed spinal posture compared with the non-biofeedback group. Lai and Shea (1999) also found improvements in both relative timing of a motor task and the retention of a motor task when bandwidth feedback was used with a 15% error magnitude range. Bandwidth feedback has shown to be important in early learning where motor programmes are formed, further supporting the findings of this study that, after approximately 13 minutes, participants reduce their reliance on biofeedback.

Current evidence in motor learning suggests that biofeedback therapy should be task-oriented, repetitive, and delivered during functionally related dynamic movement to optimize motor function improvement (Giggins et al., 2013; Huang, Wolf, & Jiping, 2006). In the current study, participants were given task-specific feedback on LS posture during the lifting task. The reduced number of feedback signals given to the BF group during the end stages of the lifting suggests that specific feedback on end range LS posture was an appropriate approach to facilitate motor learning, despite the potential negative effects of fatigue on posture during a lifting task.

Following the brief familiarisation to the biofeedback protocol that the BF group underwent, it appeared that the BF group had increased awareness of lumbar posture and significantly altered their LSF at the start of the lifting task when compared to the NBF group. Mawston et al. (2007) demonstrated a similar learning effect where participants exhibited a significantly altered, and more stable, postural response to sudden perturbation following a single exposure to loading.

4.7.3 Biofeedback and its Effects on Kinematics and Kinetics

In the current study, those participants that did not receive biofeedback showed postural changes associated with repetition and likely fatigue, i.e. they increased lumbar flexion and reduced knee flexion. Fatigue has been shown to have detrimental effects on lifting posture (e.g. decreased postural awareness and reduced spinal stability) when manual handling and this potentially increased the risk of back injury (Sparto et al., 1996; Taimela et al., 1999). The addition of biofeedback reduced the extent of lumbar and trunk flexion during the lifting task in this study. The reduced lumbar and trunk flexion was accompanied by greater knee flexion, particularly near the end of the lifting task. In contrast, significantly less knee flexion was evident in the NBF group at the end of the lifting task. These changes would indicate that the NBF group progressed from a relatively flexed knee posture to a relatively straight knee posture over time, while the BF group maintained a relatively similar peak knee flexion posture throughout. The BF group could be considered to have adopted and maintained what is often clinically defined as a 'semi-squat' lifting posture with the back slightly flexed and the hips and knees bent (Bonato et al., 2003), whereas the NBF group adopted a 'stoop' lifting posture (i.e. bent back, straighter legs) in the end stages of the lifting task.

> Consequently, the null hypothesis (2) was rejected that there would be no difference in lower limb kinematics or kinetics during a repetitive lifting task as a result of biofeedback.

Some studies have shown changes in lifting strategies in response to fatigue, with handlers shifting from a predominantly 'squat' lifting posture (with the back straight and knees bent) to a 'stoop' (with the back bent and knees straight) posture (Dolan & Adams, 1998; Potvin et al., 1991). This may be the result of a number of factors, such as impaired proprioception (Taimela et al., 1999), and reduced postural awareness (Sparto et al., 1996; Taimela et al., 1999) in response to fatigue (Dolan & Adams, 1998). It has been shown that some types of squat lifting are physiologically more demanding, with a significantly higher oxygen consumption, compared to stoop lifting (Hagen, Hallen, & Harms-Ringdahl, 1993; Kumar, 1984). Therefore, changing to a more stooped posture may be a more energy-efficient adaptation to assuage the effects of fatigue (Hagen, Harms-Ringdahl, & Hallen, 1994).

Another factor, that may have influenced changes in LS posture in the NBF group, may have been changes in proprioception with the onset of fatigue and its influence on awareness of LS posture (Panjabi, 2006; Ribeiro et al., 2011). Afferent information from muscles and ligaments to the sensorimotor cortex has been shown to diminish during fatigue (Solomonow et al., 1998; Solomonow et al., 1999), and when intrinsic feedback is impaired, greater reliance is placed on external feedback (Schmidt & Wrisberg, 2008). External feedback can be useful in maintaining task performance in situations where muscles are fatigued (Herbert et al., 2008). Whilst the current study did not measure proprioception, the results showed that, without external biofeedback, participants progressively changed their %LSF. Repeatedly loading or maintaining the lumbar spine in end range flexion has been associated with impaired proprioceptive acuity and creep (Sanchez et al., 2006). However, with the addition of external feedback, participants were able to a maintain LS posture within a range that was primarily controlled by the muscular system and avoided passive tissue creep (Dolan, Mannion, et al., 1994).

4.7.4 Spinal Loading and Risk of Injury

Estimates of bending moments acting on the passive structure of the lumbar spine showed a decrease with the use of biofeedback during a repetitive lifting task. In the current study, the bending moment resisted by the passive structures of the spine was approximately three times higher in the NBF group than the BF group at the end of the lifting task.

> Consequently, the null hypothesis (3) was rejected that there would be no difference in passive loading of the lumbar spine during a repetitive lifting task as a result of biofeedback.

A number of studies have shown an association between frequent forward bending, particularly towards end range spinal flexion, and the increased risk of LBP (Punnett, Fine, Keyserling, Herrin, & Chaffin, 1991; Ramond-Roquin et al., 2015). Gallagher et al. (2007) showed a 50 fold decrease in time to fatigue failure of the spine when flexed to end range compared to a neutral and moderately flexed spinal postures.

Dolan, Mannion, et al. (1994) found that, during a submaximal isometric lifting task, the active extensor moment of the lower erector spinae muscles (as measured by EMG activity) linearly reduced up to 80% of spinal flexion, after which their contribution decreased exponentially (Dolan, Mannion, et al., 1994). The increased loads placed on the passive structures of the spine at end ranges of lumbar flexion are likely to increase risk of ligament injury and vertebral end-plate damage (Dolan, Mannion, et al., 1994; Gallagher et al., 2007). Furthermore, it has been shown that recruitment of the posterior ligamentous system (e.g. supraspinous ligaments) in end ranges of lumbar flexion can substantially increase anterior shear forces (Potvin et al., 1991). By facilitating the reduction of frequent forward end range LSF, biofeedback is likely to reduce the recruitment of the passive, posterior ligamentous system, and thus, risk of injury.

4.7.5 Biofeedback and Perceived Physical Demands

Initial findings indicated differences in RPE for both the BF and NBF groups, with the BF group displaying significantly lower RPE scores at the end of the lifting task compared to the NBF group (Figure 4.22). After further analysis it became clear that there were individuals within the BF group with noticeably lower RPE scores compared to the other participants within that group and these were classified as outliers. It was deemed appropriate to remove three extreme outliers from the data. The identification of and subsequent removal of the three extreme outliers resulted in no significant difference in RPE scores between groups over the duration of the task (Figure 4.23). Removal of these outliners was considered justified as their RPE scores did not exceed 11 on the Borg scale (1990) throughout the task (six to 20 point scale). It is possible that the participants were unable to appropriately distinguish and rate physical exertion.

> Consequently, the null hypothesis (4) that there would be no difference in perceived physical exertion (RPE) between the BF and NBF groups was not rejected.

RPE findings are contrary to what might be expected given the different lifting strategies adopted by each group. As previously mentioned, the semi-squat lifting posture adopted by the BF group has be shown to be more physically demanding and, therefore, likely to result in increased RPE (Hagen et al., 1993).

RPE can be influenced by peripheral factors, such as local trunk muscle ischemia and fatigue, and nociceptive inputs from stretched passive structures. According to research performed by Masuda, Miyamoto, Oguri, Matsuoka, and Shimizu (2005), the erector spinae muscle thickness decreases in more flexed postures leading to ischemic changes and LBP. In more flexed postures there is also increased stretch of ligamentous structures (Panjabi, 2006). Therefore, longer periods spent in flexed postures may have led to decreased blood flow and increased nociceptive information from the stretching of ligamentous structures, contributing to increased levels of discomfort (Masuda et al., 2005; Panjabi, 2006; Watanabe, Miyamoto, Masuda, & Shimizu, 2004). Therefore, in the case of the NBF group, longer periods of end range lumbar flexion may have contributed to low back discomfort. In contrast, adopting a lifting posture with an extended lumbar spine, such as the BF group, has been shown to increase activation levels and the physiological demands on the erector spinae muscles when compared to flexed postures. It has been suggested that increased metabolic demands of the erector spinae muscles over time in less flexed postures may contribute to muscle fatigue and an increased perceived effort (Hagen et al., 1993).

Another contributing factor to the RPE results could be related to the increased lifting speed of the BF group and subsequent longer rest periods between lifts. The results show that the BF group achieved this with greater peak hip and knee extension velocities compared to the NBF group, resulting in a shorter time to complete each lift. Increasing the speed of a lift has been shown to increase bending moments acting on the spine (Lavender, Andersson, Schipplein, & Fuentes, 2003; Lavender, Li, Andersson, & Natarajan, 1999) and the risk of LBI (Alderson, Hopper, Elliott, & Ackland, 2009). In the present study, however, the LS extension velocities were lower in the BF group, with no significant differences in total bending moments acting on the spine between groups. It would, therefore, seem that postural responses to lumbar spine biofeedback result in faster lower limb kinematics without increasing lumbar spine velocity or compromising lumbar spine loading (moments).

In summary, although the BF group adopted a physically more demanding lifting strategy, this was balanced out by increases in localized pain levels and shorter rest periods between lifts in the NBF group.

4.7.6 Biofeedback: Implications for Younger, Inexperienced Handlers

Participants in the current study were young and inexperienced in manual handling. Findings of the present study relating to the NBF group are in accordance with previous results (Boocock et al., 2015) that indicate that younger and more inexperienced individuals tend to adopt a more flexed lumbar spine during repetitive lifting activities, in a range of lumbar flexion that can potentially increase their risk of injury. Epidemiological evidence would suggest that there is a higher initial onset rate of LBI in young, inexperienced workers (Van Nieuwenhuyse et al., 2004). The NBF group increased lumbar flexion to over 80% LSF after approximately five minutes of lifting and continued to increase LSF to approximately 99% of maximum at the end of the lifting task. In contrast, the BF group tended to display a slower progression at a reduced rate of %LSF and only reached a maximum of 62% LSF by the end of the lifting task. Thus biofeedback may provide a preventative management approach suitable for inexperienced younger workers entering vocations involving repetitive manual handling activities. The effectiveness of biofeedback on more experienced workers warrants further investigation. J. Lee and Nussbaum (2012) have shown that experienced handlers adopt different lifting strategies to those of novices, which may reduce the risk of LBI. Other studies suggest that experienced workers avoid extreme postural deviations and have decreased muscle activation that may serve to reduce low back loads when lifting (Keir & MacDonell, 2004; Pal, Milosavljevic, Gregory, Carman, & Callaghan, 2010). Therefore, biofeedback may provide an approach to enhance lifting postures among inexperienced manual handlers.

4.7.7 Clinical Implications

The findings of this study contribute to the body of knowledge involving the biomechanics of lifting and the effects of biofeedback. This study has implications for individuals undertaking manual handling lifting tasks, for organizations providing manual handling guidelines, and physiotherapists involved in the prevention and ongoing management of LBP, although further work is needed.

Biofeedback of the LS posture can be used as a treatment adjunct to educate clients about their lifting posture. This seems particularly important for young, inexperienced workers employed in repetitive manual handling who appear at increased risk of back injury. Without feedback, this population appear to adopt lifting postures characterized by progressive linear increases in LSF to end range, increasing the bending moment on the passive structures of the spine.

Restricting LSF during repetitive lifting is important in reducing passive loading on the musculoskeletal structures of the lumbar spine. Previous research has shown that end range LSF during a repeated lifting task predisposes the lumbar spine to increased risk of LBI due to factors such as, the decreased contribution of the active structures, decreased proprioception, and increased loads placed on the passive structures of the spine.

The fatigue associated with repetitive lifting did not appear to have a detrimental effect on the ability to control LS posture in the majority of participants. One compensatory strategy included adopting a semi-squat lifting posture, characterized by a degree of lumbar flexion coupled with hip and knee flexion during the lift. A further compensatory strategy that was adopted was a faster lifting speed. In a rehabilitation or vocational setting it would, therefore, be prudent to include power training, such as lower limb plyometric training, as part of a lumbar lifting programme.

Bandwidth feedback, as implemented in this study, appeared to be an effective motor learning adjunct. Evidence from the literature supports the use of bandwidth feedback, as this type of feedback can enhance motor learning (Butler et al., 1996), particularly with larger bandwidths (Smith et al., 1997). In clinical practice, similar feedback strategies could be used with bandwidths set to provide subjects with knowledge of correct and incorrect postural results. This could, for example, be used as part of a postural training programme.

Participants did not become reliant on biofeedback for controlling LS posture during the repetitive lifting task. This is important from a learning perspective, as the findings would suggest that being exposed to real-time postural biofeedback led to a short-term learning effect.

4.7.8 Limitations of the Study

This study was designed to be methodologically rigorous, though a number of limitations have been identified.

Firstly, the study aimed to investigate the effectiveness of biofeedback on the LS posture of participants performing a repetitive lifting activity in a laboratory environment. Whilst there are a number of similarities between this task and those performed in a work environment, there are also a number of key differences that might influence the results, such as variable work conditions and the influence co-workers may have on the person performing the lifting task. The changing nature of work, and exposure to a range of physical, psychosocial and environmental conditions can influence the way in which an individual performs a lifting activity. Therefore, extrapolating these findings to a work environment should be undertaken with caution.

Although no restrictions were placed on the lifting technique adopted by participants, aspects of the lifting task were constrained to control potential confounding factors. These included the task being restricted to symmetrical lifting with participants adopting a stationary foot position and maintaining hold on the box throughout. Further work should investigate the effects of LS posture biofeedback during complex lifting tasks (e.g. asymmetric) in realistic work environments.

Biofeedback was provided and lifting posture measured for a single 20 minute session. Additional investigation into prolonged exposure to biofeedback should be made that may be more representative of a working day, over an 8 hour period, for example.

The data from two participants were excluded from the analysis due to technical problems with the inertial sensors, where communication between the sensors and the computer was lost and resulted in missing data. In order for biofeedback systems to be used in an occupational setting they need to be user-friendly and reliable.

Participants were recruited from a mainly physiotherapy student and staff population and might not be representative of a wider cohort, particularly those occupations associated with manual handling.

Marker displacement due to skin movement and markers becoming dislodged during the lifting task may have led to errors when determining kinematics and could be considered a potential source of error. The markers were placed by three different examiners during the course of the study which could have led to some variability in the marker placement and therefore the results.

While only male participants took part in the study, the high predominance of male employees in heavy manual jobs makes the study of particular relevance to the working population.

The sensors that were worn by the participants to measure spinal posture and provide feedback were relatively large and were attached to the participant’s skin with adhesive tape. Therefore, the sensors could have impacted on the participant’s natural LS posture and lifting technique, as they could have provided additional proprioceptive feedback to those participants.

This biomechanical modelling approach is based on inverse dynamics which is a method to analyse human movement and estimate joint loading. As with all estimations of human body movement, errors may occur and cannot be avoided. Consideration should be given to more detailed and sophisticated biomechanical models which are available, that could be used, for example, to assess net loads on the spine.

No direct physiological measures were employed in the study, such as EMG or heart rate, and the assumption that the lifting protocol was fatiguing is based on the inference that the protocol in the present study was similar to other studies that have shown back muscle fatigue from this type of task.

The same examiner conducted the random allocation, data collection and analysis, therefore blinding was unable to be achieved which could have influenced the study results.

Finally, consideration should be given to the fact there was no follow-up period in the present study and, therefore, the long term effects of biofeedback could not be determined. The results of this study can therefore only be applied to situations where feedback is actively provided in real-time. Repeated sessions should be conducted to assess the effect that time and number of exposures would have on the effectiveness of biofeedback.

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

Real-time biofeedback of LS posture had a significant short-term effect on lumbar and lower limb kinematics. Biofeedback reduced the rate of progression into a more flexed LS posture during a repetitive lifting task.

There were no differences between groups in the bending moment acting on the lumbar spine, however the estimated biomechanical loads acting on the passive structures of the lower back were significantly lower in the BF group.

Participants in the BF group adopted a different lifting strategy to compensate for imposed restrictions on the lumbar spine. This strategy employed greater knee flexion and increased hip and knee extension velocities.

The amount of biofeedback decreased towards the end of the lifting task, indicating that reliance on biofeedback decreased and that a short-term learning effect occurred.

The use of biofeedback on LS posture appears an appropriate intervention to educate clients about their lifting posture and promote better postural awareness particularly for young, novice lifters.

Biofeedback did not lead to a perception of more exertion, as measured using RPE, in this group of participants. Despite the effects of fatigue, participants were able to control lumbar posture. Participants adopted a lifting strategy that involved higher peak knee and hip extension velocities and longer rest periods. This strategy may have provided participants with micro-pauses and longer time to recover between lifts.

Biofeedback could be implemented during a repetitive lifting activity to limit the potentially detrimental fatigue-related changes that would otherwise occur.

5.2 Recommendations

This study identified five key areas for future research.

I. Additional studies should be conducted to establish the effectiveness of biofeedback on spinal posture in the occupational setting during a fatiguing activity. Longer periods of feedback could be investigated and how fatigue over a working day could, for example, influence posture.

II. Future studies should investigate the optimal protocol for biofeedback, such as duration and frequency of feedback. A follow up period should be included in order to establish the temporal effect of biofeedback.

III. Further research is required to investigate the use and effectiveness of different sensors and techniques of feedback provision, e.g. vibratory and virtual reality.

IV. Blinding of assessors should be considered to improve the quality of the experimental design.

V. Consideration should be given to usability and cost-effectiveness of biofeedback for use in clinical practice and workplace settings, perhaps looking to wearable technology and smartphones.

References

Accident Compensation Corporation. (2016). *Claims for work-related injuries in 2015*. Retrieved 24/08/2016, 2016, from http://www.stats.govt.nz/browse_for_stats/health/injuries/InjuryStatistics_HOTP14/Tables.aspx#provisional

Adams, J. A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. *Psychological Bulletin, 101*(1), 41. Retrieved from www.apa.org.ezproxy.aut.ac.nz/pubs/journals/bul/index.aspx

Alderson, J., Hopper, L., Elliott, B., & Ackland, T. (2009). Risk Factors for Lower Back Injury in Male Dancers Performing Ballet Lifts. *Journal of Dance Medicine & Science, 13*(3), 83-89. Retrieved from http://www.iadms.org/?page=47

Arjmand, N., Shirazi-Adl, A., & Bazrgari, B. (2006). Wrapping of trunk thoracic extensor muscles influences muscle forces and spinal loads in lifting tasks. *Clinical Biomechanics, 21*(7), 668-675. doi:10.1016/j.clinbiomech.2006.03.006

Astin, J. A., Beckner, W., Soeken, K., Hochberg, M. C., & Berman, B. (2002). Psychological interventions for rheumatoid arthritis: A meta-analysis of randomized controlled trials. *Arthritis Care & Research, 47*(3), 291-302. doi:10.1002/art.10416

Basmajian, J. V. (1982). Clinical use of biofeedback in rehabilitation. *Psychosomatics, 23*(1), 67-73. Retrieved from http://www.psychosomaticsjournal.com/

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *arXiv preprint arXiv:1406.5823*.

Bigos, S. J., Spengler, D. M., Martin, N. A., Zeh, J., Fisher, L., & Nachemson, A. (1986). Back Injuries in Industry: A Retrospective Study: III. Employee-related Factors. *Spine, 11*(3), 252-256. Retrieved from http://journals.lww.com/spinejournal/pages/default.aspx

Bonato, P., Ebenbichler, G. R., Roy, S. H., Lehr, S., Posch, M., Kollmitzer, J., & Della Croce, U. (2003). Muscle fatigue and fatigue-related biomechanical changes during a cyclic lifting task. *Spine, 28*(16), 1810-1820. doi:10.1097/01.BRS.0000087500.70575.45

Boocock, M. G., Jackson, J., Burton, A. K., & Tillotson, K. (1994). Continuous measurement of lumbar posture using flexible electrogoniometers. *Ergonomics, 37*(1), 175-185.

Boocock, M. G., Mawston, G. A., & Taylor, S. (2015). Age-related differences do affect postural kinematics and joint kinetics during repetitive lifting. *Clinical Biomechanics, 30*, 136-143. doi:10.1016/j.clinbiomech.2014.12.010

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scandinavian Journal of Work, Environment & Health*, 55-58. Retrieved from http://www.sjweh.fi

Borg, G., & Kaijser, L. (2006). A comparison between three rating scales for perceived exertion and two different work tests. *Scandinavian Journal of Medicine & Science in Sports, 16*(1), 57-69.

Borkan, J., Van Tulder, M., Reis, S., Schoene, M. L., Croft, P., & Hermoni, D. (2002). Advances in the field of low back pain in primary care: a report from the fourth international forum. *Spine, 27*(5), E128-E132. Retrieved from http://journals.lww.com/spinejournal/pages/default.aspx

Bouisset, S., & Zattara, M. (1987). Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. *Journal of Biomechanics, 20*(8), 735-742. Retrieved from https://www.journals.elsevier.com/journal-of-biomechanics

Breen, P. P., Nisar, A., & Ólaighin, G. (2009). Evaluation of a single accelerometer based biofeedback system for real-time correction of neck posture in computer users [Conference Paper]. *31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society: Engineering the Future of Biomedicine, EMBC 2009*, 7269-7272. doi:10.1109/IEMBS.2009.5334726

Burgess-Limerick, R., & Abernethy, B. (1997). Toward a quantitative definition of manual lifting postures. *Human Factors, 39*(1), 141-148. Retrieved from http://hfs.sagepub.com

Butler, M. S., Reeve, T. G., & Fischman, M. G. (1996). Effects of the instructional set in the bandwidth feedback paradigm on motor skill acquisition. *Research Quarterly for Exercise and Sport, 67*(3), 355-359. Retrieved from http://www.tandfonline.com.

Callaghan, J. P., & McGill, S. M. (2001). Intervertebral disc herniation: studies on a porcine model exposed to highly repetitive flexion/extension motion with compressive force. *Clinical Biomechanics, 16*(1), 28-37. doi:10.1016/S0268-0033(00)00063-2

Cappozzo, A., Cappello, A., Croce, U. D., & Pensalfini, F. (1997). Surface-marker cluster design criteria for 3-D bone movement reconstruction. *IEEE Transactions on Biomedical Engineering, 44*(12), 1165-1174.

Çelenay, S. T., Kaya, D. O., & Özüdogru, A. (2015). Spinal postural training: Comparison of the postural and mobility effects of electrotherapy, exercise, biofeedback trainer in addition to postural education in university students. *Journal of Back and Musculoskeletal Rehabilitation, 28*(1), 135-144. doi:10.3233/BMR-140501

Charry, E., Umer, M., & Taylor, S. (2011). Design and validation of an ambulatory inertial system for 3-D measurements of low back movements Symposium conducted at the meeting of the Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2011 Seventh International Conference on doi:10.1109/ISSNIP.2011.6146618

Cole, M. H., & Grimshaw, P. N. (2003). Low back pain and lifting: a review of epidemiology and aetiology. *Work (Reading, Mass.), 21*(2), 173-184. Retrieved from http://www.iospress.nl/journal/work/

Crider, A. B., & Glaros, A. G. (1999). A meta-analysis of EMG biofeedback treatment of temporomandibular disorders. *Journal of orofacial pain, 13*(1), 135-145. Retrieved from http://www.quintpub.com/journals/jop/gp.php?journal_name=JOP&name_abbr=JOP

Crisco, I., & Panjabi, M. M. (1991). The intersegmental and multisegmental muscles of the lumbar spine: a biomechanical model comparing lateral stabilizing potential. *Spine, 16*(7), 793-799. Retrieved from http://journals.lww.com/spinejournal/pages/default.aspx

da Costa, B. R., & Vieira, E. R. (2010). Risk factors for work-related musculoskeletal disorders: a systematic review of recent longitudinal studies. *American Journal Of Industrial Medicine, 53*(3), 285-323. doi:10.1002/ajim.20750

Dagenais, S., Caro, J., & Haldeman, S. (2008). A systematic review of low back pain cost of illness studies in the United States and internationally. *The Spine Journal, 8*(1), 8-20. doi:10.1016/j.spinee.2007.10.005

Dankaerts, W., O'Sullivan, P. B., Burnett, A., & Straker, L. (2006). Altered patterns of superficial trunk muscle activation during sitting in nonspecific chronic low back pain patients: importance of subclassification. *Spine, 31*(17), 2017-2023. doi:10.1097/01.brs.0000228728.11076.82

De Luca, C. J. (1997). Low back pain: a major problem with low priority. *Journal of Rehabilitation Research and Development, 34*(4), 8-13.

Dean, A., & Dean, S. (2006). A pilot study investigating the use of the Orthosense Posture Monitor during a real-world moving and handling task. *Journal of Bodywork and Movement Therapies, 10*(3), 220-226. doi:10.1016/j.jbmt.2005.10.007

Dempster, W. P. (1955). *Space requirements of the seated operator.* Wright Patterson Airforce Base, Fairborn

Dillingham, T. (1995). Evaluation and management of low back pain: an overview. *State of the Art Reviews, 9*(3), 559-574.

Dolan, P., & Adams, M. A. (1998). Repetitive lifting tasks fatigue the back muscles and increase the bending moment acting on the lumbar spine. *Journal of Biomechanics, 31*(8), 713-721. doi:10.1016/S0021-9290(98)00086-4

Dolan, P., Earley, M., & Adams, M. A. (1994). Bending and compressive stresses acting on the lumbar spine during lifting activities. *Journal of Biomechanics, 27*(10), 1237-1248. doi:10.1016/0021-9290(94)90277-1

Dolan, P., Mannion, A. F., & Adams, M. A. (1994). Passive tissues help the back muscles to generate extensor moments during lifting. *Journal of Biomechanics, 27*(8), 1077-1085. doi:10.1016/0021-9290(94)90224-0

Downs, S. H., & Black, N. (1998). The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *Journal of Epidemiology and Community Health, 52*(6), 377-384. doi:10.1136/jech.52.6.377

Ernst, E. (2003). Systematische reviews zu biofeedback (Systematic reviews of biofeedback) [German]. *Physikalische Medizin, Rehabilitationsmedizin, Kurortmedizin 2003 Dec;13(6):321-324*. doi:10.1055/s-2003-45436

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175-191. doi:10.3758/bf03193146

Forwell, L. A., & Carnahan, H. (1996). Proprioception During Manual Aiming in Individuals With Shoulder Instability and Controls. *Journal of Orthopaedic & Sports Physical Therapy, 23*(2), 111-119. doi:10.2519/jospt.1996.23.2.111

Gallagher, S., Marras, W. S., Litsky, A. S., Burr, D., Landoll, J., & Matkovic, V. (2007). A comparison of fatigue failure responses of old versus middle-aged lumbar motion segments in simulated flexed lifting. *Spine, 32*(17), 1832-1839. doi:10.1097/01.brs.0000259812.75138.c0

Giggins, O. M., Persson, U. M., & Caulfield, B. (2013). Biofeedback in rehabilitation. *Journal of NeuroEngineering and Rehabilitation, 10*, 60-60. doi:10.1186/1743-0003-10-60

Goetzel, R. Z., Hawkins, K., Ozminkowski, R. J., & Wang, S. (2003). The Health and Productivity Cost Burden of the “Top 10” Physical and Mental Health Conditions Affecting Six Large U.S. Employers in 1999. *Journal of Occupational and Environmental Medicine, 45*(1), 5-14. Retrieved from http://journals.lww.com./joem/pages/default.aspx

Gracovetsky, S., Newman, N., Pawlowsky, M., Lanzo, V., Davey, B., & Robinson, L. (1995). A Database for Estimating Normal Spinal Motion Derived From Noninvasive Measurements. *Spine, 20*(9), 1036-1046. Retrieved from http://journals.lww.com/spinejournal/pages/default.aspx

Granata, K. P., & Gottipati, P. (2008). Fatigue influences the dynamic stability of the torso. *Ergonomics, 51*(8), 1258-1271. doi:10.1080/00140130802030722

Guadagnoli, M. A., & Lee, T. D. (2004). Challenge Point: A Framework for Conceptualizing the Effects of Various Practice Conditions in Motor Learning. *Journal Of Motor Behavior, 36*(2), 212-224. doi:10.3200/JMBR.36.2.212-224

Guyatt, G. H., Oxman, A. D., Schünemann, H. J., Tugwell, P., & Knottnerus, A. (2011). GRADE guidelines: a new series of articles in the Journal of Clinical Epidemiology. *Journal of clinical epidemiology, 64*(4), 380-382. doi:10.1016/j.jclinepi.2010.09.011

Ha, T.-H., Saber-Sheikh, K., Moore, A. P., & Jones, M. P. (2013). Measurement of lumbar spine range of movement and coupled motion using inertial sensors – A protocol validity study. *Manual Therapy, 18*(1), 87-91 85p. doi:10.1016/j.math.2012.04.003

Hagen, K. B., Hallen, J., & Harms-Ringdahl, K. (1993). Physiological and subjective responses to maximal repetitive lifting employing stoop and squat technique. *Eur J Appl Physiol Occup Physiol, 67*(4), 291-297. doi:10.1007/BF00357625

Hagen, K. B., Harms-Ringdahl, K., & Hallen, J. (1994). Influence of lifting technique on perceptual and cardiovascular responses to submaximal repetitive lifting. *Eur J Appl Physiol Occup Physiol, 68*(6), 477-482. doi:10.1007/BF00599516

Hanavan, J. E. P. (1966). A personalized mathematical model of the human body. *Journal of Spacecraft and Rockets, 3*(3), 446-448. doi:10.2514/3.28474

Henry, S. M., & Westervelt, K. C. (2005). The Use of Real-Time Ultrasound Feedback in Teaching Abdominal Hollowing Exercises to Healthy Subjects. *Journal of Orthopaedic & Sports Physical Therapy, 35*(6), 338-345. doi:10.2519/jospt.2005.35.6.338

Herbert, W. J., Heiss, D. G., & Basso, D. M. (2008). Influence of feedback schedule in motor performance and learning of a lumbar multifidus muscle task using rehabilitative ultrasound imaging: a randomized clinical trial. *Physical Therapy, 88*(2), 261-269. doi:10.2522/ptj.20060308

Hides, J. A., Richardson, C. A., & Jull, G. A. (1998). Use of real-time ultrasound imaging for feedback in rehabilitation. *Manual Therapy, 3*(3), 125-131. doi:10.1016/S1356-689X(98)80002-7

Hodges, P. W. (1999). Is there a role for transversus abdominis in lumbo-pelvic stability? *Manual Therapy, 4*(2), 74-86. doi:http://dx.doi.org/10.1054/math.1999.0169

Hoogendoorn, W. E., van Poppel, M. N., Bongers, P. M., Koes, B. W., & Bouter, L. M. (2000). Systematic review of psychosocial factors at work and private life as risk factors for back pain. *Spine, 25*(16), 2114-2125. Retrieved from http://journals.lww.com/spinejournal/pages/default.aspx

Howarth, S. J., & Mastragostino, P. (2013). Use of Kinetic and Kinematic Data to Evaluate Load Transfer as a Mechanism for Flexion Relaxation in the Lumbar Spine. *Journal of Biomechanical Engineering, 135*(10), 101004-101004-101006. doi:10.1115/1.4025112

Hoy, D., Bain, C., Williams, G., March, L., Brooks, P., Blyth, F., . . . Buchbinder, R. (2012). A systematic review of the global prevalence of low back pain. *Arthritis & Rheumatology, 64*(6), 2028-2037. doi:10.1002/art.34347

Hoy, D., Brooks, P., Blyth, F., & Buchbinder, R. (2010). The Epidemiology of low back pain. *Best Practice & Research Clinical Rheumatology, 24*(6), 769-781. doi:https://doi.org/10.1016/j.berh.2010.10.002

Huang, H., Wolf, S. L., & Jiping, H. (2006). Recent developments in biofeedback for neuromotor rehabilitation. *Journal of NeuroEngineering and Rehabilitation, 3*(1), 1. doi:10.1186/1743-0003-3-11

Ihlebaek, C., Hansson, T. H., Laerum, E., Brage, S., Eriksen, H. R., Holm, S. H., . . . Indahl, A. (2006). Prevalence of low back pain and sickness absence: a "borderline" study in

Norway and Sweden. *Scandinavian Journal Of Public Health, 34*(5), 555-558. doi:10.1080/14034940600552051

Ikegami, T., Hirashima, M., Osu, R., & Nozaki, D. (2012). Intermittent Visual Feedback Can Boost Motor Learning of Rhythmic Movements: Evidence for Error Feedback Beyond Cycles. *Journal of Neuroscience, 32*. doi:dx.doi.org/10.1523/4230-11.2012

Intolo, P., Carman, A., Milosavljevic, S., Abbott, J., & Baxter, G. (2010). The Spineangel®: examining the validity and reliability of a novel clinical device for monitoring trunk motion. *Manual Therapy, 15*(2), 160-166. doi:10.1016/j.math.2009.10.002

Katz, J. N. (2006). Lumbar disc disorders and low-back pain: socioeconomic factors and consequences. *Journal of Bone & Joint Surgery, American Volume, 88-A*(1), 21-24. doi:10.2106/JBJS.E.01273

Keir, P. J., & MacDonell, C. W. (2004). Muscle activity during patient transfers: a preliminary study on the influence of lift assists and experience. *Ergonomics, 47*(3), 296-306. doi:10.1080/0014013032000157922

Kelsey, J. L., Githens, P. B., White, A. A., Holford, T. R., Walter, S. D., O'Connor, T., . . . Calogero, J. A. (1984). An epidemiologic study of lifting and twisting on the job and risk for acute prolapsed lumbar intervertebral disc. *J Orthop Res, 2*(1), 61-66. doi:10.1002/jor.1100020110

Krause, N., & Ragland, D. R. (1994). Occupational Disability Due to Low Back Pain: A New Interdisciplinary Classification Based on a Phase Model of Disability. *Spine, 19*(9), 1011-1020. Retrieved from http://journals.lww.com/spinejournal/pages/default.aspx

Kuiper, J. I., Burdorf, A., Verbeek, J. H. A. M., Frings-Dresen, M. H. W., van der Beek, A. J., & Viikari-Juntura, E. R. A. (1999). Epidemiologic evidence on manual materials handling as a risk factor for back disorders:a systematic review. *International Journal of Industrial Ergonomics, 24*(4), 389-404. doi:https://doi.org/10.1016/S0169-8141(99)00006-2

Kumar, S. (1984). The physiological cost of three different methods of lifting in sagittal and lateral planes. *Ergonomics, 27*(4), 425-433. doi:10.1080/00140138408963506

Lai, Q., & Shea, C. H. (1999). Bandwidth Knowledge of Results Enhances Generalized Motor Program Learning. *Research Quarterly for Exercise and Sport, 70*(1), 79-83. doi:10.1080/02701367.1999.10607734

Lavender, S., Andersson, G. B. J., Schipplein, O. D., & Fuentes, H. J. (2003). The effects of initial lifting height, load magnitude, and lifting speed on the peak dynamic L5/S1 moments. *International Journal of Industrial Ergonomics, 31*(1), 51-59. doi:http://dx.doi.org/10.1016/S0169-8141(02)00174-9

Lavender, S., Li, Y. C., Andersson, G. B. J., & Natarajan, R. N. (1999). The effects of lifting speed on the peak external forward bending, lateral bending, and twisting spine moments. *Ergonomics, 42*(1), 111-125. doi:10.1080/001401399185838

Leboeuf-Yde, C., Yashin, A., & Lauritzen, T. (1996). Does smoking cause low back pain? Results from a population-based study. *Journal of Manipulative and Physiological Therapeutics, 19*(2), 99-108.

Lee, J., & Nussbaum, M. A. (2012). Experienced workers exhibit distinct torso kinematics/kinetics and patterns of task dependency during repetitive lifts and lowers. *Ergonomics, 55*(12), 1535-1547. doi:10.1080/00140139.2012.723139

Lee, R. Y., Laprade, J., & Fung, E. (2003). A real-time gyroscopic system for three-dimensional measurement of lumbar spine motion. *Medical Engineering & Physics, 25*(10), 817-824. doi:10.1016/S1350-4533(03)00115-2

Linton, S. J., Boersma, K., Jansson, M., Overmeer, T., Lindblom, K., & Vlaeyen, J. W. S. (2008). A randomized controlled trial of exposure in vivo for patients with spinal pain reporting fear of work-related activities. *European Journal of Pain, 12*(6), 722-730. doi:10.1016/j.ejpain.2007.11.001

Lou, E., Lam, G. C., Hill, D. L., & Wong, M. S. (2012). Development of a smart garment to reduce kyphosis during daily living. *Medical and Biological Engineering and Computing, 50*(11), 1147-1154. doi:10.1007/s11517-011-0847-7

Ma, Y., & Bai, X. F. (2014). Vibration control system of precision dicing saw machine based on neural network method. *Applied Mechanics and Materials, 577*, 228-231. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84905012897&partnerID=40&md5=e80c8a4c6a8016f108fed42ad5208944 doi:10.4028/www.scientific.net/AMM.577.228

Maduri, A., & Wilson, S. E. (2009). Lumbar position sense with extreme lumbar angle. *Journal of Electromyography and Kinesiology, 19*(4), 607-613. doi:10.1016/j.jelekin.2008.03.004

Magnusson, M. L., Chow, D. H., Diamandopoulos, Z., & Pope, M. H. (2008). Motor control learning in chronic low back pain. *Spine, 33*(16), E532-E538. doi:10.1097/BRS.0b013e31817dfd9a

Magnusson, M. L., Granqvist, M., Jonson, R., Lindell, V., Lundberg, U., Wallin, L., & Hansson, T. (1990). The loads on the lumbar spine during work at an assembly line. The risks for fatigue injuries of vertebral bodies. *Spine, 15*(8), 774-779. doi:10.1097/00007632-199008010-00007

Manchikanti, L., Singh, V., Falco, F. J., Benyamin, R. M., & Hirsch, J. A. (2014). Epidemiology of low back pain in adults. *Neuromodulation: Technology at the Neural Interface, 17*(S2), S3-S10. doi:10.1111/ner.12018

Mani, R., Milosavljevic, S., & Sullivan, S. J. (2010). The effect of occupational whole-body vibration on standing balance: A systematic review. *International Journal of Industrial Ergonomics, 40*(6), 698-709. doi:http://dx.doi.org/10.1016/j.ergon.2010.05.009

Maniadakis, N., & Gray, A. (2000). The economic burden of back pain in the UK. *Pain, 84*(1), 95-103. doi:https://doi.org/10.1016/S0304-3959(99)00187-6

Mannion, A., & Troke, M. (1999). A comparison of two motion analysis devices used in the measurement of lumbar spinal mobility. *Clinical Biomechanics, 14*(9), 612-619. doi:10.1016/S0268-0033(99)00017-0

Marras, W. S., Davis, K. G., Heaney, C. A., Maronitis, A. B., & Allread, W. G. (2000). The Influence of Psychosocial Stress, Gender, and Personality on Mechanical Loading of the Lumbar Spine. *Spine, 25*(23), 3045-3054. Retrieved from http://journals.lww.com/spinejournal/pages/default.aspx

Marras, W. S., Lavender, S. A., Ferguson, S. A., Splittstoesser, R. E., & Yang, G. (2010). Quantitative dynamic measures of physical exposure predict low back functional impairment. *Spine, 35*(8), 914-923. doi:10.1097/BRS.0b013e3181ce1201

Marras, W. S., Lavender, S. A., Leurgans, S. E., Fathallah, F. A., Ferguson, S. A., Allread, W. G., & Rajulu, S. L. (1995). Biomechanical risk factors for occupationally related low back disorders. *Ergonomics, 38*(2), 377-410. doi:10.1080/00140139508925111

Marras, W. S., Lavender, S. A., Leurgans, S. E., Rajulu, S. L., Allread, W. G., Fathallah, F. A., & Ferguson, S. A. (1993). The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury. *Spine, 18*(5), 617-628. doi:10.1097/00007632-199304000-00015

Masuda, T., Miyamoto, K., Oguri, K., Matsuoka, T., & Shimizu, K. (2005). Relationship between the thickness and hemodynamics of the erector spinae muscles in various lumbar curvatures. *Clinical Biomechanics, 20*(3), 247-253. doi:https://doi.org/10.1016/j.clinbiomech.2004.10.008

Mawston, G. A., McNair, P. J., & Boocock, M. G. (2007). The effects of prior exposure, warning, and initial standing posture on muscular and kinematic responses to sudden loading of a hand-held box. *Clinical Biomechanics, 22*(3), 275-281. doi:10.1016/j.clinbiomech.2006.10.007

McAlpine, R., Bettany-Saltikov, J., & Warren, J. (2009). Computerized back postural assessment in physiotherapy practice: Intra-rater and inter-rater reliability of the MIDAS system. *Journal of Back and Musculoskeletal Rehabilitation, 22*(3), 173-178. doi:10.3233/BMR-2009-0231

McGill, S. M. (2007). *Lumbar spine stability: mechanism of injury and restabilization*. Philadelphia: Lippincott, Williams & Wilkins.

McGill, S. M. (2015). *Low Back Disorders* (Third ed.). Philadelphia: Human Kinetics.

Mehta, J. P., Lavender, S. A., & Jagacinski, R. J. (2014). Physiological and biomechanical responses to a prolonged repetitive asymmetric lifting activity. *Ergonomics, 57*(4), 575-588. doi:10.1080/00140139.2014.887788

Montgomery, T., Boocock, M. G., & Hing, W. (2011). The effects of spinal posture and pelvic fixation on trunk rotation range of motion. *Clinical Biomechanics, 26*(7), 707-712. doi:10.1016/j.clinbiomech.2011.02.010

Moreland, J. D., Thomson, M. A., & Fuoco, A. R. (1998). Electromyographic biofeedback to improve lower extremity function after stroke: A meta-analysis. *Archives of Physical Medicine and Rehabilitation, 79*(2), 134-140. doi:10.1016/S0003-9993(98)90289-1

Muslim, K., Bazrgari, B., Hendershot, B., Toosizadeh, N., Nussbaum, M. A., & Madigan, M. L. (2013). Disturbance and recovery of trunk mechanical and neuromuscular behaviors following repeated static trunk flexion: Influences of duration and duty cycle on creep-induced effects. *Applied ergonomics, 44*(4), 643-651. doi:https://doi.org/10.1016/j.apergo.2012.12.004

Nachemson, A. L. (1992). Newest Knowledge of Low Back Pain A Critical Look. *Clinical Orthopaedics and Related Research, 279*, 8-20. Retrieved from http://www.springer.com/medicine/orthopedics/journal/11999

NIOSH. (1997). Musculoskeletal disorders and workplace factors; a critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back. Retrieved from https://stacks.cdc.gov/view/cdc/21745

Norman, R., Wells, R., Neumann, P., Frank, J., Shannon, H., & Kerr, M. (1998). A comparison of peak vs cumulative physical work exposure risk factors for the reporting of low back pain in the automotive industry. *Clinical Biomechanics (Bristol, Avon), 13*(8), 561-573. doi:10.1016/S0268-0033(98)00020-5

O'Neil, M., Berkman, N., Hartling, L., Chang, S., Anderson, J., Motu'apuaka, M., . . . McDonagh, M. S. (2014). Observational evidence and strength of evidence domains: case examples. *Systematic reviews, 3*(1), 1. doi:10.1186/2046-4053-3-35

O'Sullivan, K., O'Sullivan, L., Campbell, A., O'Sullivan, P., & Dankaerts, W. (2012). Towards monitoring lumbo-pelvic posture in real-life situations: Concurrent validity of a novel posture monitor and a traditional laboratory-based motion analysis system. *Manual Therapy, 17*(1), 77-83. doi:http://dx.doi.org/10.1016/j.math.2011.09.006

O'Sullivan, K., O'Sullivan, L., Dankaerts, W., & O'Sullivan, P. (2010). Technologies to monitor and provide feedback on spinal posture in low back pain: A review Symposium conducted at the meeting of the L. Proceedings of the Irish Ergonomics Society Annual Conference. Limerick, Ireland: Irish Ergonomics Society

O'Sullivan, P. (2005). Diagnosis and classification of chronic low back pain disorders: Maladaptive movement and motor control impairments as underlying mechanism. *Manual Therapy, 10*(4), 242-255. doi:10.1016/j.math.2005.07.001

O'Sullivan, P., Burnett, A., Floyd, A. N., Gadsdon, K., Logiudice, J., Miller, D., & Quirke, H. (2003). Lumbar Repositioning Deficit in a Specific Low Back Pain Population. *Spine, 28*(10), 1074-1079. doi:10.1097/01.brs.0000061990.56113.6f

Onate, J. A., Guskiewicz, K. M., & Sullivan, R. J. (2001). Augmented Feedback Reduces Jump Landing Forces. *Journal of Orthopaedic & Sports Physical Therapy, 31*(9), 511-517. doi:10.2519/jospt.2001.31.9.511

Pal, P., Milosavljevic, S., Gregory, D. E., Carman, A. B., & Callaghan, J. P. (2010). The influence of skill and low back pain on trunk postures and low back loads of shearers. *Ergonomics, 53*(1), 65-73. doi:10.1080/00140130903389027

Panjabi, M. M. (2006). A hypothesis of chronic back pain: ligament subfailure injuries lead to muscle control dysfunction. *European Spine Journal: Official Publication Of The*

European Spine Society, The European Spinal Deformity Society, And The European Section Of The Cervical Spine Research Society, 15(5), 668-676. doi:10.1007/s00586-005-0925-3

Parkinson, R. J., Beach, T. A. C., & Callaghan, J. P. (2004). The time-varying response of the in vivo lumbar spine to dynamic repetitive flexion. *Clinical Biomechanics, 19*(4), 330-336. doi:https://doi.org/10.1016/j.clinbiomech.2004.01.002

Parnianpour, M., Nordin, M., Kahanovitz, N., & Frankel, V. (1988). 1988 Volvo award in biomechanics. The triaxial coupling of torque generation of trunk muscles during isometric exertions and the effect of fatiguing isoinertial movements on the motor output and movement patterns. *Spine, 13*(9), 982-992.

Pearcy, M. J. (1985). Stereo radiography of lumbar spine motion. *Acta Orthopaedica Scandinavica, 56*(212), 1-45. doi:10.3109/17453678509154154

Potvin, J. R., Norman, R. W., & McGill, S. M. (1991). Reduction in anterior shear forces on the L4L5 disc by the lumbar musculature. *Clinical Biomechanics, 6*(2), 88-96.

Punnett, L., Fine, L. J., Keyserling, W. M., Herrin, G. D., & Chaffin, D. B. (1991). Back disorders and nonneutral trunk postures of automobile assembly workers. *Scandinavian Journal of Work, Environment & Health*(5), 337. doi:10.5271/sjweh.1700

Ramond-Roquin, A., Bodin, J., Serazin, C., Parot-Schinkel, E., Ha, C., Richard, I., . . . Roquelaure, Y. (2015). Biomechanical constraints remain major risk factors for low back pain. Results from a prospective cohort study in French male employees. *The Spine Journal, 15*(4), 559-569. doi:https://doi.org/10.1016/j.spinee.2013.05.040

RCoreTeam. (2017). *A Language and Environment for Statistical Computing*. Retrieved from http://www.R-project.org/

Ribeiro, D., Sole, G., Abbott, J. H., & Milosavljevic, S. (2011). Systematic review: Extrinsic feedback and management of low back pain: A critical review of the literature [Review Article]. *Manual Therapy, 16*, 231-239. doi:10.1016/j.math.2010.12.001

Ribeiro, D., Sole, G., Abbott, J. H., & Milosavljevic, S. (2014). The effectiveness of a lumbopelvic monitor and feedback device to change postural behavior: A feasibility randomized controlled trial. *Journal of Orthopaedic and Sports Physical Therapy, 44*(9), 702-711. doi:10.2519/jospt.2014.5009

Ronchi, A. J., Lech, M., Taylor, N., & Cosic, I. (2008). A reliability study of the new Back Strain Monitor based on clinical trials Symposium conducted at the meeting of the Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conference of the IEEE

Roy, S. H., De Luca, C. J., & Casavant, D. A. (1989). Lumbar muscle fatigue and chronic lower back pain. *Spine, 14*(9), 992-1001.

Sanchez, D., Adams, M. A., & Dolan, P. (2006). Spinal proprioception and back muscle activation are impaired by spinal “creep” but not by fatigue. *Journal of Biomechanics, 39*(Supplement 1), S33. doi:https://doi.org/10.1016/S0021-9290(06)83002-2

Schepers, H. M. (2009). *Ambulatory assessment of human body kinematics and kinetics*. University of Twente, The Netherlands. doi:10.3990/1.9789036528443

Schmidt, R. A., Lange, C., & Young, D. E. (1990). Optimizing summary knowledge of results for skill learning. *Human Movement Science, 9*(3), 325-348. doi:10.1016/0167-9457(90)90007-Z

Schmidt, R. A., & Wrisberg, C. A. (2008). Motor learning and performance: A situation-based learning approach. *20*(3), 125-129.

Sheeran, L., Sparkes, V., Busse, M., & van Deursen, R. (2010). Preliminary study: reliability of the spinal wheel. A novel device to measure spinal postures applied to sitting and standing. *European Spine Journal, 19*(6), 995-1003. doi:10.1007/s00586-009-1241-0

Shumway-Cook, A., & Woollacott, M. (2007). *Motor control: translating research into clinical practice.* (3 ed.). Philadelphia: Lippincott Williams & Wikins

Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2013). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. *Psychonomic Bulletin & Review, 20*(1), 21-53. doi:10.3758/s13423-012-0333-8

Smith, P. J., Taylor, S. J., & Withers, K. (1997). Applying bandwidth feedback scheduling to a golf shot. *Research Quarterly for Exercise and Sport, 68*(3), 215-221. Retrieved from http://www.tandfonline.com

Snider, K. T., Snider, E. J., Degenhardt, B. F., Johnson, J. C., & Kribs, J. W. (2011). Palpatory Accuracy of Lumbar Spinous Processes Using Multiple Bony Landmarks. *Journal of Manipulative and Physiological Therapeutics, 34*(5), 306-313. doi:http://dx.doi.org/10.1016/j.jmpt.2011.04.006

Solomonow, M. (2012). Neuromuscular manifestations of viscoelastic tissue degradation following high and low risk repetitive lumbar flexion. *Journal of Electromyography and Kinesiology, 22*(2), 155-175. doi:https://doi.org/10.1016/j.jelekin.2011.11.008

Solomonow, M., Zhou, B.-H., Harris, M., Lu, Y., & Baratta, R. V. (1998). The Ligamento-Muscular Stabilizing System of the Spine. *Spine, 23*(23), 2552-2562. Retrieved from http://journals.lww.com/spinejournal/pages/default.aspx

Solomonow, M., Zhou, B. H., Baratta, R. V., Lu, Y., & Harris, M. (1999). Biomechanics of increased exposure to lumbar injury caused by cyclic loading: Part 1. Loss of reflexive muscular stabilization. *Spine, 24*(23), 2426-2434. doi:10.1097/00007632-199912010-00003

Solomonow, M., Zhou, B. H., Lu, Y., & King, K. B. (2012). Acute repetitive lumbar syndrome: A multi-component insight into the disorder. *Journal of Bodywork and Movement Therapies, 16*(2), 134-147. doi:https://doi.org/10.1016/j.jbmt.2011.08.005

Sparto, P. J., Parnianpour, M., Reinsel, T. E., & Simon, S. (1997). The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test. *The Journal Of Orthopaedic And Sports Physical Therapy, 25*(1), 3-12. doi:10.2519/jospt.1997.25.1.3

Sparto, P. J., Parnianpour, M., Reinsel, T. E., & Simon, S. R. (1996). The adaptations to fatigue during a repetitive lifting test Symposium conducted at the meeting of the Biomedical Engineering Conference, 1996., Proceedings of the 1996 Fifteenth Southern IEEE Conference doi:10.1109/SBEC.1996.493147

Taimela, S., Kankaanpää, M., & Luoto, S. (1999). The effect of lumbar fatigue on the ability to sense a change in lumbar position. A controlled study. *Spine, 24*(13), 1322-1327.

Tate, J. J., & Milner, C. E. (2010). Real-Time Kinematic, Temporospatial, and Kinetic Biofeedback During Gait Retraining in Patients: A Systematic Review. *Physical Therapy, 90*(8), 1123-1134. doi:10.2522/ptj.20080281

Thompson, R. C., & Cullom, S. J. (2006). Issues regarding radiation dosage of cardiac nuclear and radiography procedures [journal article]. *Journal of Nuclear Cardiology, 13*(1), 19-23. doi:10.1016/j.nuclcard.2005.11.004

Trott, P. H., Pearcy, M. J., Ruston, S. A., Fulton, I., & Brien, C. (1996). Three-dimensional analysis of active cervical motion: the effect of age and gender. *Clinical Biomechanics, 11*(4), 201-206. doi:http://dx.doi.org/10.1016/0268-0033(95)00072-0

Van Nieuwenhuyse, A., Fatkhutdinova, L., Verbeke, G., Pirenne, D., Johannik, K., Somville, P. R., . . . Masschelein, R. (2004). Risk factors for first-ever low back pain among workers in their first employment. *Occupational medicine, 54*(8), 513-519. doi:10.1093/occmed/kqh091

Van Tulder, M. W., Koes, B. W., & Bouter, L. M. (1997). Conservative treatment of acute and chronic nonspecific low back pain: a systematic review of randomized controlled trials of the most common interventions. *Spine, 22*(18), 2128-2156. Retrieved from http://journals.lww.com/spinejournal/pages/default.aspx

van Vliet, P. M., & Wulf, G. (2006). Extrinsic feedback for motor learning after stroke: What is the evidence? *Disability and Rehabilitation, 28*(13-14), 831-840. doi:10.1080/09638280500534937

Vignais, N., Miezal, M., Bleser, G., Mura, K., Gorecky, D., & Marin, F. (2013). Innovative system for real-time ergonomic feedback in industrial manufacturing. *Applied ergonomics, 44*(4), 566-574. doi:10.1016/j.apergo.2012.11.008

Vos, T., Allen, C., Arora, M., Barber, R. M., Bhutta, Z. A., Brown, A., . . . Chen, A. Z. (2016). Global, regional, and national incidence, prevalence, and years lived with disability for 310 diseases and injuries, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *The Lancet, 388*(10053), 1545-1602. doi:10.1016/S0140-6736(16)31678-6

Waddell, G., & Burton, A. K. (2001). Occupational health guidelines for the management of low back pain at work: evidence review. *Occupational medicine, 51*(2), 124-135. doi:10.1093/occmed/51.2.124

Waddell, G., Somerville, D., Henderson, I., & Newton, M. (1992). Objective clinical evaluation of physical impairment in chronic low back pain. *Spine, 17*(6), 617-628. Retrieved from http://journals.lww.com/spinejournal/pages/default.aspx

Watanabe, K., Miyamoto, K., Masuda, T., & Shimizu, K. (2004). Use of Ultrasonography to Evaluate Thickness of the Erector Spinae Muscle in Maximum Flexion and Extension of the Lumbar Spine. *Spine, 29*(13), 1472-1477. doi:10.1097/01.brs.0000128755.84693.10

Waters, T. R., Putz-Anderson, V., & Garg, A. (1994). Applications manual for the revised NIOSH lifting equation. Retrieved from https://stacks.cdc.gov/view/cdc/5434

Winter, D. A. (2009). *Biomechanics and motor control of human movement*. New York: John Wiley & Sons.

Wolf, S. L. (1983). Electromyographic biofeedback applications to stroke patients a critical review. *Physical Therapy, 63*(9), 1448-1459. Retrieved from http://ptjournal.apta.org

Wong, W. Y., & Wong, M. S. (2008). Smart garment for trunk posture monitoring: A preliminary study. *Scoliosis, 3*(1). doi:10.1186/1748-7161-3-7

Worth, S., Henry, S., & Bunn, J. (2007). Real-time ultrasound feedback and abdominal hollowing exercises for people with low back pain. *New Zealand Journal of Physiotherapy, 35*(1), 4. Retrieved from http://physiotherapy.org.nz/professional-development/publications/nz-journal-of-physiotherapy/

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., . . . Stokes, I. (2002). ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—Part I: ankle, hip, and spine. *Journal of Biomechanics, 35*(4), 543-548. doi:10.1016/S0021-9290(01)00222-6

Wu, G., van der Helm, F. C. T., Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., . . . Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics, 38*(5), 981-992. doi:10.1016/j.jbiomech.2004.05.042

Appendices

Appendix A: Example of Generic Search Terms

1. feedback

2. biofeedback

3. postural feedback

4. perceptual feedback

5. 1 or 2 or 3 or 4

6. accelerometer*

7. electrogoniometer*

8. inclinometer*

9. isotrak

10. fastrak

11. inert*

12. sensor*

13. “lumbar motion monitor”

14. 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13

15. spin*

16. lordo*

17. lumb*

18. "low* back"

19. "low* spin*"

20. 11 or 12 or 12 or 14 or 15

21. 5 and 14 and 16

Appendix B: Downs and Black Appraisal Tool

Critiquing tool for evaluating the quality of experimental and quasi-experimental studies ((Downs & Black, 1998)

Title:

Author(s):

Journal: of Biomedicine Vol: Pages: Year:

SCORE:

Modified Downs and Black Tool

Reporting

1	***Is the hypothesis/aim/objective of the study clearly described?***	Y (1) / N (0)
2	***Are the main outcomes to be measured clearly described in the Introduction or Methods section?***	Y (1) / N (0)
	If the main outcomes are first mentioned in the Results section, the question should be answered no.	
3	***Are the characteristics of the patients included in the study clearly described?***	Y (1) / N (0)
	In cohort studies and trials, inclusion and/or exclusion criteria should be given. In case-control studies, a case-definition and the source for controls should be given.	
4	***Are the interventions of interest clearly described?***	Y (1) / N (0)

Treatments and placebo (where relevant) that are to be compared should be clearly described.

5	***Are the distributions of principal confounders in each group of subjects to be compared clearly described?***	Y (2) / P (1) / N (0)
	A list of principal confounders is provided.	
6	***Are the main findings of the study clearly described?*** Simple outcome data (including denominators and numerators) should be reported for all major findings so that the reader can check the major analyses and conclusions. (This question does not cover statistical tests which are considered below)	Y (1) / N (0)
7	***Does the study provide estimates of the random variability in the data for the main outcomes?***	Y (1) / N (0)
	In non-normally distributed data the inter-quartile range of results should be reported. In normally distributed data the standard error, standard deviation or confidence intervals should be reported. If the distribution of the data is not described, it must be assumed that the estimates used were appropriate and the answer should be answered yes	

8	***Have all important adverse events that may be a consequence of the intervention been reported?***	Y (1) / N (0)
	This should be answered yes if the study demonstrates that there was a comprehensive attempt to measure adverse events. (A list of possible adverse events is provided).	
9	***Have the characteristics of patients lost to follow-up been described?***	Y (1) / N (0)
	This should be answered yes where there were no losses to follow-up or where losses to follow-up were so small that findings would be unaffected by their inclusion. This should be answered no where a study does not report the number of patients lost to follow-up.	
10	***Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?***	Y (1) / N (0)
External validity		
11	***Were the subjects asked to participate in the study representative of the entire population from which they were recruited?***	Y (1) / N (0) / UTD (0)
	The study must identify the source population for patients and describe how the patients were selected. Patients would be representative if they comprised the entire source population, an	

unselected sample of consecutive patients, or a random sample. Random sampling is only feasible where a list of all members of the relevant population exists. Where a study does not report the proportion of the source population from which patients are derived, the question should be answered as unable to determine.

12	***Were those subjects who were prepared to participate representative of the entire population from which they were recruited?***	Y (1) / N (0) / UTD (0)

The proportion of those asked who agreed should be stated. Validation that the sample was representative would include demonstrating that the distribution of the main confounding factors was the same in the study sample and the source population.

13	***Were the activities, equipment and surroundings where the participants were measured representative of the majority of activities, equipment and surroundings that the majority of participants would encounter?***	Y (1) / N (0) / UTD (0)

Internal validity - bias

14	***Was an attempt made to blind study subjects to the intervention they have received?*** For studies where the patients would have no way of knowing which intervention they received, this should be answered yes.	Y (1) / N (0) / UTD (0)
15	***Was an attempt made to blind those measuring the main outcomes of the intervention?***	Y (1) / N (0) / UTD (0)
16	***If any of the results of the study were based on "data dredging", was this made clear?*** Any analyses that had not been planned at the outset of the study should be clearly indicated. If no retrospective unplanned subgroup analysis were reported, then answer yes.	Y (1) / N (0) / UTD (0)
17	***In trials and cohort studies, do the analyses adjust for different lengths of follow-up of patients, or in case-control studies, is the time period between the intervention and outcome the same for cases and controls?*** Where follow-up was the same for all study patients the answer should yes. If different lengths of follow-up were adjusted for by, for example, survival analysis the answer should be yes. Studies where differences in follow-up are ignored should be answered no.	Y (1) / N (0) / UTD (0)

18	***Were the statistical tests used to assess the main outcomes appropriate?*** The statistical techniques used must be appropriate to the data. For example non-parametric methods should be used for small sample sizes. Where little statistical analysis has been undertaken but where there is no evidence of bias, the question should be answered yes. If the distribution of the data (normal or not) is not described it must be assumed that the estimates used were appropriate and the question should be answered yes.	Y (1) / N (0) / UTD (0)
19	***Was compliance with the intervention/s reliable?*** Where there was non-compliance with the allocated treatment or where there was contamination of one group, the question should be answered no. For studies where the effect of misclassification was likely to bias any association to the null, the question should be answered no.	Y (1) / N (0) / UTD (0)
20	***Were the main outcome measures used accurate (valid and reliable)?*** For studies where the outcome measures are clearly described, the question should be answered yes. For studies which refer to other work or that demonstrates the outcome measures are accurate, the question should be answered as yes.	Y (1) / N (0) / UTD (0)

Internal validity - confounding (selection bias)

21	***Were the patients in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited from the same population?***	Y (1) / N (0) / UTD (0)
	For example, patients for all comparison groups should be selected from the same hospital. The question should be answered unable to determine for cohort and case-control studies where there is no information concerning the source of patients included in the study.	
22	***Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same time?***	Y (1) / N (0) / UTD (0)
	For a study which does not specify the time period over which patients were recruited, the question should be answered as unable to determine.	
23	***Were study subjects randomised to intervention groups?***	Y (1) / N (0) / UTD (0)
	Studies which state that subjects were randomised should be answered yes except where method of randomisation would not ensure random allocation. For example, alternate allocation would score no because it is predictable.	

24	***Was the randomised intervention assignment concealed from both patients and health care staff until***	Y (1) / N (0) / UTD (0)
	recruitment was complete and irrevocable?	
	All non-randomised studies should be answered no. If assignment was concealed from patients but not from staff, it should be answered no.	
25	***Was there adequate adjustment for confounding in the analyses from which the main findings were***	Y (1) / N (0) / UTD (0)
	drawn?	
	This question should be answered no for trials if: the main conclusions of the study were based on analyses of treatment rather than intention to treat; the distribution of known confounders in the different treatment groups was not described; or the distribution between known confounders differed between treatment groups but no was taken into account in the analyses. In non-randomised studies if the effect of the main confounders was not investigated or confounding was demonstrated but no adjustment was made in the final analyses the question should be answered as no.	

26	***Were losses of patients to follow-up taken into account?*** If the numbers of patients lost to follow-up are not reported the question should be answered as unable to determine. If the proportion lost to follow-up was too small to affect t he main findings, the question should be answered as yes.	Y (1) / N (0) / UTD (0)

Power

27	***Was there a power calculation undertaken or an adequate explanation of why sample size was chosen?***	Y (1) / N (0)

Note: Y = Yes, N = No, P = Partially, UTD = Unable to determine

Appendix C: Ethical Approval from Auckland University of Technology Ethics Committee (AUTEC)

AUT UNIVERSITY TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

A U T E C

S E C R E T A R I A T

9 July 2014

Mark Boocock

Faculty of Health and Environmental Sciences

Dear Mark

Re Ethics Application: **14/196 The use of inertial motion sensors for assessing human movement, and its use as a tool for providing biofeedback when performing repetitive lifting: its effects on physical and physiological responses in young individuals.**

Thank you for submitting your application for ethical review. I am pleased to confirm that the Auckland University of Technology Ethics Committee (AUTEC) has approved your ethics application for three years until 7 July 2014.

AUTEC wishes to commend you on the thoroughness of the application.

AUTEC notes that the words 'prior to the completion of data collection' needs to be added to the withdrawal statement in the Information Sheet.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 7 July 2017;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 7 July 2017 or on completion of the project;

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence.

AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply within their.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O'Connor

Executive Secretary

Auckland University of Technology Ethics Committee

Cc: Yanto Naude; Grant Mawston

Appendix D: Advertisement for Recruitment

An investigation of repetitive lifting postures and biofeedback

Volunteers required!

- This is part of a research project investigating repetitive lifting postures and the use of biofeedback (giving you information about your spine when lifting).
- Participants must be males aged between 18 and 35 years old.
- We welcome participants without a history of back pain.
- You should not have any other muscle, joint, or neurological disorder.
- You should not have received any spinal or abdominal surgery in the past.
- You are required to be able to speak and understand English.

For more information please contact:

Contact
Yanto Naude
yanto.naude@aut.ac.nz
09 921 9999 ext 7074

Contact
Yanto Naude
yanto.naude@aut.ac.nz
09 921 9999 ext 7074

Contact
Yanto Naude
yanto.naude@aut.ac.nz
09 921 9999 ext 7074

Contact
Yanto Naude
yanto.naude@aut.ac.nz
09 921 9999 ext 7074

Contact
Yanto Naude
yanto.naude@aut.ac.nz
09 921 9999 ext 7074

Contact
Yanto Naude
yanto.naude@aut.ac.nz
09 921 9999 ext 7074

Contact
Yanto Naude
yanto.naude@aut.ac.nz
09 921 9999 ext 7074

Contact
Yanto Naude
yanto.naude@aut.ac.nz
09 921 9999 ext 7074

***North Shore Times* Advertisement**

AUT University: An investigation of repetitive lifting postures and biofeedback – Volunteers required.

We are undertaking a research project investigating how the postures used during repetitive lifting and can be influenced by biofeedback (i.e. providing information about your spine when lifting). Male participants between the ages of 18 and 35 years without a history of pack pain are required for this study. You must: not have any muscle, joint or neurological disorder, or have received any spinal or abdominal surgery; and be able to speak and understand English. If you are interested and would like further information please contact:

Yanto Naude, yanto.naude@aut.ac.nz, 09 921 9999 ext 7074

Appendix E: Participant Information Sheet

Participant Information Sheet

Date Information Sheet Produced:

18th December 2015

Do you need an interpreter?

English	I wish to have an interpreter	Yes	No
Maori	E hiahia ana ahau ki tetahi Kaiwhakamaori / Kaiwhakapakeha korero	Ae	Kao
Samoan	Oute mana'o ia iai se fa'amatala upu	Ioe	Leai
Tongan	Oku ou fiema'u ha fakatonulea	Io	Ikai
Cook Island	Ka inangaro au I tetai tangata uri reo	Ae	Kare
Niuean	Fia manako au ke fakaaoga e taha tagata fakahokohoko kupu	E	Nakai

Project Title

The effect of repetitive lifting on postural, psychophysical, and physiological responses of young individuals.

An Invitation

I am Yanto Naude, a researcher at the Health and Rehabilitation Research Centre at Auckland University of Technology.

You are invited to participate in a research study. Participation is completely voluntary and you may withdraw from the study at any time prior to the completion of data collection without giving a reason or being disadvantaged.

Your participation in this study will be stopped should any harmful effects appear.

What is the purpose of this research?

This study aims to investigate how repetitive lifting affects perceptual effort, body motion, and physiological measures (heart rate, and muscle activity) in young males.

Repetitive lifting has been associated with the increased risk of low back pain in industry. This study will allow us to gather information about how the body responds to repetitive lifting.

The results of this study will be analysed and written up for publication in a medical journal.

No material that could personally identify you will be used in any reports on this study unless your personal approval is given for the dissemination of results to specific persons (please see the section below titled "How will my privacy be protected?" for more information on privacy issues).

Are you eligible to participate in this project?

If you are a male between the age of 18 and 35 years old and have no musculoskeletal or cardiovascular condition that may affect your performance in lifting task (described below) you are eligible to participate in this study. You are not eligible to participate in this study if you:

- Have any medical conditions (eg. cardiovascular disease, neurological or psychological disease, cancer, respiratory disease).
- Have had a low back injury within the last 6 months.
- Have a chronic low back injury (low back pain for greater than 3 months).
- Are under 18 or over 35 years of age.
- Are female.
- Have any other severe musculoskeletal condition that may inhibit lower limb movement.

What will happen in this research?

This study involves one sessions of approximately 2 hours.

Lifting test

The lifting test session will begin with a general warm-up. Shiny markers will be placed on various bony prominences on your lower limbs and trunk. These are used to track your movements and posture. The lifting task will require you to lift a box weighing 13 kg to the beat of a metronome, until you are fatigued, or you are advised by the researcher to stop. During the lifting task your heart rate and lifting posture will be measured. The investigator will also ask you to rate how exerted you feel at regular intervals throughout the lifting task using a perceived exertion scale. You can withdraw from the lifting task at any stage.

A video camera will record the lifting task in order that 3 physiotherapists can assess your lifting posture. These therapists and the researchers will be the only people who will see the video recording.

If you have any musculoskeletal or cardiovascular condition that may affect your performance in the lifting tasks, you will be excluded from participating in this project.

All measurements will be undertaken at the Health and Rehabilitation Research Centre, Akoranga Campus, Auckland University of Technology. The session will last for approximately two hours.

What are the discomforts and risks?

- There are some risks associated with repetitive lifting to fatigue. This test will require maximal effort, stressing the heart, lungs and musculoskeletal system and with increasing exercise intensity there is a risk of a cardiovascular incident or musculoskeletal injury.

- There is a risk of delayed onset muscle soreness. As the name suggests this is soreness of the muscles that begins one or more days after exercise. This can occur following exercise which you are not used to. While this can be uncomfortable the symptoms usually go away after one or two days.

How will these discomforts and risks be alleviated?

- The researchers involved in testing are trained in cardiopulmonary resuscitation (CPR) and have a set protocol for dealing with a cardiovascular event. Access to defibrillation equipment is available via the Student Health Clinic located adjacent to the HRRC.

- The tests undertaken in the current study have been used for research on healthy populations within your age group with no reported adverse effects.

- During the test session should you feel any chest or arm pain, feel dizzy, faint, shortness of breath or nauseous, or have excessive discomfort please advise the researcher and you will be withdrawn from the experiment. If you feel any discomfort following the experiment, you should inform the investigator who will provide you with advice and options regarding the management of any discomfort.

What are the benefits?

Data from the lifting session will provide information about how repetitive lifting affects your work capacity.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

Any information we collect will not be able to be identified as belonging to you. All data collected will only be identified by a number. The researchers will be the only people who have access to this information. All information will be kept in a secure room and in a locked filing cabinet.

What are the costs of participating in this research?

There is no financial cost to you to participate in this research. It will take approximately 2 and ½ hours.

What opportunity do I have to consider this invitation?

You have one week to decide whether you wish to take part in the study. You have a right to choose not to participate. If you agree to take part you are free to withdraw from the study at anytime, without having to give a reason.

How do I agree to participate in this research?

If you agree to participate in the study please complete the attached consent form.

Will I receive feedback on the results of this research?

If you wish to have a copy of the results of this research, please inform the supervisor, Mark Boocock. This will be available after the study is completed and published.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Mark Boocock*, mark.boocock@aut.ac.nz,* Ext 7167

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Madeline Banda, *madeline.banda@aut.ac.nz* , 921 9999 ext 8044.

Whom do I contact for further information about this research?

Please feel free to contact the researcher if you have any questions about this study.

Researcher Contact Details:

Yanto Naude, yanto.naude@aut.ac.nz, 921 9999 ext 7074.

This study has received approval from the AUT Ethics Committee (AUTEC) which was granted on the 9th of July 2014. Reference number 14/196.

Appendix F: Consent Form

Consent to Participation in Research

Title of project: **The effects of repetitive lifting on postural, psychophysical, and physiological responses in young and middle aged individuals.**

Researchers: **Grant Mawston, Mark Boocock, Peter McNair, and Yanto Naudé**

- I have read and understood the information provided about this research project.
- I have had an opportunity to ask questions and have them answered.
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. If I withdraw, I understand that all relevant video tapes and data will be destroyed.
- I have not had a history of low back pain within the last six months; previous spinal surgery; any cardiovascular or neurological condition where aerobic stress is likely to cause harm; and any musculoskeletal injury that may affect performance.
- I agree to take part in this research.
- I would like to receive a summary of the research Yes No

Participant signature: ....

Participant name:

Participant Contact Details (if appropriate):

………………………………………………………………………………………..

………………………………………………………………………………………..

………………………………………………………………………………………..

Date:

This study has received approval from the AUT Ethics Committee (AUTEC) which was granted on the 9th of July 2014. Reference number 14/196.

Appendix G: Rating of Perceived Exertion Checklist

Time (mins)	**RPE**	**Remark**	**Time (mins)**	**RPE**	**Remark**
0			11		
1			12		
2			13		
3			14		
4			15		
5			16		
6			17		
7			18		
8			19		
9			20		
10			21		