ISBN 978-82-326-2056-2 (printed ver.)
ISBN 978-82-326-2057-9 (electronic ver.)
ISSN 1503-8181

Doctoral theses at NTNU, 2016:356

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Printed by NTNU Grafisk senter

Postural strategi, muskelaktivering og variasjon av muskelaktivering i korsryggen i sammenheng med å stå eller sitte i lengre tid hos pasienter med kroniske korsryggsmerter

Bakgrunn og hensikt

De aller fleste mennesker vil i løpet av livet oppleve en episode med vond rygg. Som oftest finner en ingen spesifikk årsak til korsryggsmertene, og tilstanden er i de fleste tilfeller over innen 6 uker uten behandling. Hos noen få vedvarer korsryggsmertene ut over 6 uker, og vond rygg i mer enn 12 uker regnes som en kronisk tilstand. Aktiviteter i dagliglivet som å sitte, stå i ro eller husarbeid, gir for mange økt korsryggsmerte. Typisk for disse dagligdagse aktivitetene er at de er statiske og krever lite muskelkraft.

Hovedmålet med avhandlingen er å få bedre innsikt i muskelfunksjon, postural strategi og trøtthet i korsryggen hos pasienter med kroniske korsryggsmerter sammenlignet med friske i forbindelse med lavnivå muskel aktivering i samband med sitting og ståing i lengre perioder.

Materiale og metode

Datamateriale er fra to observasjonsstudier, en studie med langvarig sitting (30 minutt) og en studie med langvarig ståing (15 minutt). Studiepopulasjonen i begge studiene bestod av pasienter med kroniske korsryggsmerter og friske kontrollpersoner. Under sittingen ble muskelaktiveringsmønstre på begge sider i korsryggen registrert med en fler-kanals overflate elektromyografi teknikk (HDsEMG) samtidig som stillingen for overkropp og bekken ble registret. Før og etter sittingen ble smerteintensitet og opplevd anstrengelse registret. I studien med langvarig ståing ble muskelaktiveringsmønster fra utvalgte muskler i sete, rygg og mage registret med tradisjonell bipolar overflate elektromyografi, mens måten en stod på ble registrert med to kraftplattformer. For å undersøke hvilken innvirkning langvarig ståing har på individet ble det før og etter ståing utført en rekke tester for å måle styrke, propriosepsjon, motorisk- og postural kontroll i tillegg til smerteintensitet og opplevd anstrengelse etter ståingen.

Hovedfunn og konklusjoner

I artikkel I er det sett på om muskeltrøtthet oppstår i dyp og overfladisk korsryggmuskulatur under 30 minutter sitting, sammenheng mellom muskeltrøtthet og variasjon i muskelaktivering og om det er kjønnsforskjeller i dette. Vi fant en relativt høyere aktiveringsgrad i overfladisk korsryggmuskulatur sammenlignet med dypere muskulatur. Underveis i sittingen økte aktiveringsgraden noe både i overfladisk og dyp muskulatur, samtidig som deltagerne opplevde sittingen som mer anstrengende etter hvert. Vi fant en sammenheng mellom høyere frekvens på variasjonen i aktivering av korsryggmuskler mellom venstre og høyre side og tegn på lokal muskeltrøtthet og opplevd tretthet. Det var ingen kjønnsforskjell i resultatene fra studien.

I artikkel II er det sett på om variasjonen på muskelaktiviteten i korsryggmuskler er forskjellig hos personer med kroniske korsryggsmerter sammenlignet med friske. Vi fant at pasienter med kroniske korsryggsmerter har samme mønster på variasjon av muskelaktiveringen som friske til tross for at pasientene satt mer urolig. Mange pasienter klarte ikke å sitte i 30 minutter, noe som resulterte i gjennomsnittlig kortere sittetid i gruppen med pasienter. Resultatene støtter eksistensen av redusert toleranse for sitting og indikerer at pasienter med kroniske ryggsmerter har vanskelig for å slappe av i muskler som er blitt aktivert.

I artikkel III ble det undersøkt om pasienter med kroniske korsryggsmerter har en annen postural strategi og -kontroll under langvarig ståing enn hos friske kontrollpersoner, og om pasientene ble mer affisert av ståingen. Vi fant at pasientene hadde en normal postural strategi under ståingen med økt variasjon i den stående stillingen pga økt muskelskjelett ubehag,

korsryggsmerte og følelse av anstrengelse og trøtthet. Pasientene ble ikke mer affisert av ståingen siden de hadde samme endring i styrke, propriosepsjon, motorisk- og postural kontroll etter ståingen som friske, men pasientene opplevde ståingen som mer anstrengende og mer smertefull.
Basert på disse tre artiklene kan det konkluderes med at variasjon i muskelaktivitet i korsryggmuskler har sammenheng med utvikling av muskeltrøtthet. Denne sammenhengen er lik hos pasienter med kroniske korsryggsmerte og hos friske kontroll personer. Pasienter med kroniske korsryggsmerter synes å ha vansker med å slappe av i muskler som er blitt aktivert og har redusert toleranse for sitting og ståing over tid. Pasienter har en normal postural strategi under ståing og blir ikke mer affisert av langvarig ståing, men opplever ståing som mer anstrengende og får mer vondt i korsryggen underveis.

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Finasieringskilde: Sykehuset i Vestfold

Abstract

Most people will experience low back pain (LBP) at some point in life. Usually no specific cause can be found to the LBP. Most episodes of low back pain are self-limiting were patients symptoms are usually recovered within 6 weeks without specific treatment. However, in some people the LBP persists, and after 12 weeks the condition are labeled as chronic LBP (cLBP). When performing housework or daily activities such as sitting and standing, cLBP patients frequently experience an aggravation the LBP. These activities are associated with low biomechanical load and low level isometric muscle work. The overall objective of this thesis was to gain insight in muscle functioning, postural strategies and fatigue in the lumbar region during low level isometric muscle contractions related to longer periods of sitting and standing in chronic low back pain (cLBP) patients compared to healthy control subjects (HCs).

Materials and methods

The data of this thesis is based on two observational studies; a study of prolonged sitting (30 minutes) and a study of prolonged standing (15 minutes). The study population consisted of cLBP patients and HCs. During sitting the muscle activation patterns on both sides of the lower back was recorded with a multi-channel surface electromyography technique (HDsEMG), while the position of the trunk and pelvis were registered. Measures of pain intensity and perceived exertion were recorded before and after the sitting.
During prolonged standing the muscle activation pattern from selected muscles at the hip (gluteus medius), back (erector spina) and stomach (rectus abdominis and external oblique) was collected with traditional bipolar surface electromyography, while the amount of body sway and the shift of body weight from one leg to the other was recorded with two force platforms. In order to investigate the effect of prolonged standing on the individual, a series of tests was performed before and after prolonged standing; trunk extension and flexion strength, reposition error (proprioception), motor- and postural control. Further, the pain intensity before and after prolonged standing and perceived exertion after standing was collected.

Main findings and conclusions

In paper I, the aim was to explore if muscle fatigue occurred in deep and superficial lumbar musculature during sitting, and whether fatigue was related to the variability in muscle activation and whether there was gender differences. We found that higher frequencies of alternating activation between the left and right sides lumbar muscles was associated with signs of muscle fatigue and experienced fatigue. There was no gender difference in the results from the study.
In Article II, the purpose was to explore whether the variability in muscle activity in lumbar muscles differed in cLBP patients compared to HCs during sustained quiet sitting. The variability in lumbar muscle activation was found to be similar in cLBP patients, despite observations of increased variability in sitting position in cLBP patients. Due to increased perception of musculoskeletal discomfort and pain, many cLBP patients prematurely ended the sitting, which resulted in on average shorter sitting time.

In Article III, the main aim was investigate whether patients with chronic low back pain have a different postural strategy and control during prolonged standing than HCs, and whether the patients were more affected by standing. We found that patients had a normal postural strategy during prolonged standing with increased variability in the standing posture due to increased musculoskeletal discomfort, pain and perceived exertion. Patients was not more affected by prolonged standing, since similar change in strength, proprioception, motor- and postural control was observed in cLBP patients compared to HCS after prolonged standing , although patients rated the standing as more strenuous and painful.

Based on these three articles can be concluded that variation in muscle activity in lumbar muscles are related to the development of muscle fatigue. This relationship is similar in cLBP patients and in HCs. The cLBP patients seem to have difficulties to relax muscles after activation and have reduced tolerance for sitting and standing over time. Patients are not more affected by prolonged standing, but experience standing as more strenuous and painful.

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Preface

The work of this thesis was financed by Vestfold Hospital Trust, clinic physical medicine and rehabilitation, Kysthospitalet and was carried out at the Department of Human Movement Science, Faculty of Social Sciences and Technology Management, and the Department of Neuroscience, Faculty of Medicine, NTNU.

This thesis could not have been completed without help of a number of people whom I would like to express my gratitude and appreciation.

- To my main supervisor, Professor Karin Roeleveld. This work would not been possible without your advice, encouragement, feedback and countless revisions of manuscripts.

- To my co-supervisor, Professor Aage Indahl. You are the main reason for me entering the world of science. You have taught me what is worth knowing about low back pain.

- To co-author Helene Austein for valuable contributions to data collection and preparation of paper III.

- To the administration and staff at Clinic physical medicine and rehabilitation - Kysthospitalet at Vestfold Hospital Trust, for giving me the opportunity to carry out this project.

- To Anika Aakerøy Jordbru, head of R/D department at Kysthospitalet, thank you for encouragement and support throughout the process of finalising the thesis.

- Friends and colleges at Kysthospitalet for all your contributions to the thesis.

- All the people that participated in the studies.

Last, but not least, I'm most grateful to my love Ingrid, who have always supported my work and taken care of all family business when I have spent long hours at office finishing this thesis. Very special thanks are owed to Iver, Iril and Ingvild. Thank you for remembering me of what is important in life.

List of papers

This thesis is based on the following papers:

Paper I: Ringheim I, Indahl A and Roeleveld K. (2014). **Alternating activation is related to fatigue in lumbar muscles during sustained sitting.** J Electromyogr Kinesiol 24(3): 380-386

Paper II: Ringheim I, Indahl A and Roeleveld K. **Reduced muscle activity variability in lumbar extensor muscles during sustained sitting in individuals with chronic low back pain.**
(Submitted: Plos One)

Paper III: Ringheim I, Austein H, Indahl A and Roeleveld K. (2015). **Postural strategy and trunk muscle activation during prolonged standing in chronic low back pain patients.** Gait Posture 42(4): 584-589.

Abbreviations:

LBP	Low back pain
cLBP	Chronic low back pain
COM	Centre of mass
COP	Centre of pressure
EMG	Electromyography
sEMG	Surface electromyography
HDsEMG	High density surface electromyography
MU	Motor unit
HC	Healthy control subject
FRP	Flexion relaxation phenomenon
FRR	Flexion relaxation ratio
ODI	Oswestry disability index
TSK	Tampa scale of kinesiophobia
RPE	Rating of perceived exertion
NPRS	Numeric pain rating scale
RE	Reposition error
RMS	Root mean square
COV	Coefficient of variation
SD	Standard deviation
CCT	Correlation coefficient of the total HDsEMG grid
MDF	Median frequency
IED	Inter electrode distance
BMI	Body mass index

1.0 Introduction

Low back pain (LBP) is a common health complaint. The lifetime prevalence is reported to be as high as 84%, thus most people will experience LBP at some point in their life (Balague, Mannion, Pellise, & Cedraschi, 2012). Based on exclusion of a specific cause or pathology during clinical examination, approximately 90 % of LBP patients are diagnosed to have a "non-specific low back pain" not related to serious diseases and considered to be a self-limiting condition (Koes, van Tulder, & Thomas, 2006). However, in some patients the pain persists and progresses into a chronic phase of low back pain (cLBP).

From a clinical standpoint LBP patients seems to employ many different coping strategies. Some prefer to be inactive or either laying down or sitting still while others like to move around, and when standing still shift weight from one leg to the other. Quite often they have guarded movements during walking or when bending (Geisser, Haig, Wallbom, & Wiggert, 2004; van der Hulst, Vollenbroek-Hutten, Rietman, & Hermens, 2010). In general, it is a common clinical observation that cLBP patients seem to have low tolerance for work or daily activities involving low level static muscle activation like during washing-up and vacuum-cleaning. Decreased range of motion and velocity during trunk flexion is often observed in LBP patients (Marras & Wongsam, 1986; Shum, Crosbie, & Lee, 2010; van Wingerden, Vleeming, & Ronchetti, 2008). This may indicate an alteration in how muscles are activated. The absence of a specific cause to LBP may create an uncertainty of what LBP represents, which may influence conscious and unconscious cognitive processes and affect how muscles are recruited (strategy). Brief intervention (BI), a one session cognitive, clinical examination coupled to education program, designed to remove uncertainty and give the patient an understanding that the spine is strong and will not suffer any injury through activity, has shown to be a beneficial treatment for non-specific chronic low back pain (Brox et al., 2008). Consequently, at least some of the low back pain may be attributed to altered behavioural, movement- and muscle activation strategy related to the individual knowledge and beliefs about their LBP.

For decades the alterations observed in muscle activation in patients suffering from low back pain has been argued to be compensatory for reduced spinal stability (G. L. Moseley, Hodges, & Gandevia, 2002; van Dieën, Selen, & Cholewicki, 2003), and specific physical treatments has been developed to restore (core) muscle functioning and spinal stability. However, no specific treatment has shown to be superior in treating the non-specific low back pain (Airaksinen et al., 2006; Macedo, Maher, Latimer, & McAuley, 2009).

It is well documented that patients with persisting common low back pain demonstrates poor performance in in tests involving medium to high biomechanical load (Demoulin, Crielaard, & Vanderthommen, 2007; Roy, De Luca, & Casavant, 1989). However, in real life there are many activities with low biomechanical load like e.g. during sitting and standing that challenges cLBP patients during daily life (Breivik, Collett, Ventafridda, Cohen, & Gallacher, 2006). There is limited knowledge of how cLBP patients handle daily life activities such as sitting and standing. This forms the basis for this thesis.

1.1 Classification, definitions and prevalence of low back pain

Low back pain (LBP) is defined as pain in the posterior aspects of the body from the lower margin of the twelfth rib to the lower gluteal folds, with or without pain referred to the leg(s) that is severe enough to limit usual activities for more than one day (Dionne et al., 2008). LBP is a descriptive diagnosis of where the patient have pain, and the recommended diagnostic procedure is to perform a diagnostic triage, where patients are categorized into one of the three categories "serious spinal pathology", "nerve root" or "nonspecific LBP" (Koes et al., 2010). In clinical practice as well as in the literature, nonspecific low back pain can be classified as acute (< 6 weeks), subacute (>6 weeks and < 12 weeks) and chronic (> 12 weeks) based on reported duration of symptoms (Koes et al., 2006). In this thesis chronic low back pain (cLBP) is defined as low back pain with symptoms lasting for more than 12 weeks duration.

LBP affects persons at all ages, from childhood and adolescence (Balague, Troussier, & Salminen, 1999) to elderly (Bressler, Keyes, Rochon, & Badley, 1999). The point prevalence of low back pain is up 33 %, 1-year prevalence up to 65 % and lifetime prevalence up to 84 % (Airaksinen et al., 2006). After a first time episode of back pain, up to 78 % experience a relapse of pain. There is little scientific evidence of the prevalence of chronic nonspecific low back pain, but it has been estimated to approximately 23 % and that about 12 % of the population is disabled by it (Airaksinen et al., 2006). Specific causes of low back pain (e.g. infection, tumour, osteoporosis, ankylosing spondylitis, fracture, inflammatory process, radicular syndrome or cauda equina syndrome) are rare (< 15 %).

1.2 Functional characteristics of the lumbar spine

The lumbar spine is a complex anatomical structure. It consists of five separate vertebras conjoined with three separate joints to form a movement segment(Bogduk, 2005). To meet the needs in daily life, the lumbar spine and its vertebrae must be free to move in multiple

directions, and several ligaments and muscles and their fascia are directly or indirectly connected to the vertebras in a complex way to control and move the conjoined vertebrae, (Bogduk, 2005). The lumbar spine is surrounded by a network of muscles of variable size which each have capability to exert forces on the spinal motion segments. The smallest lumbar muscles are the intersegmental muscles (e.g. the interspinalis and intertransversarii medialis) which main function may be seen act as "adjusters" and fine-tune movements made by the larger muscles (Bogduk, 2005). The lumbar multifidus muscles are the largest and most medial of the lumbar muscles. Shortest fascicles (laminar fibres) span 2 motion segments while the bulk of the multifidus have longer fascicles and acts polysegmental. The multifidus arises from each of the spinous processes in the lumbar spine from which several fascicles arise with a common tendon and diverge caudally to attach into mammilary processes, the iliac crest and the sacrum (Bogduk, 2005). Along with the intersegmental muscles, this network of lumbar muscles has potential to adjust the loading on lumbar segments and hence play a role in load distribution, load transfer and control of movements. The numerous lumbar muscles provide a pool of possible motor solutions that may be recruited to suit the need of movements of the lumbar spine in daily life. The numerous joints and muscles form a redundant set of effectors and solutions to perform the required tasks. This anatomic system in the lumbar spine is controlled in a complex way (Holm, Indahl, & Solomonow, 2002). The sensorimotor control integrates afferent information from muscles, ligaments and intervertebral discs into efferent motor neuron signals in a sophisticated system, where information from e.g. an intervertebral disc or zygapophysial joint activates muscles at adjacent levels and on the contralateral side (Holm et al., 2002).

1.3 Postural control

In this thesis, posture is defined as the habitually assumed position of the human body when standing or sitting (Horak, 2009). Postural control is the part of motor control involved in maintaining a upright position against gravity (Massion, 1994). It involves neural control of postural equilibrium (balance) and orientation of the body (Horak, 2009; Massion, 1994). In order to maintain balance, sensory and motor strategies are integrated to keep the body's center of mass (COM) over its base of support (BoS). Although neural control of posture involves most of the nervous system and body segments, it generally operates at an automatic, unconscious and non-voluntary level. During stance humans constantly make small corrections to upright body position called postural sway. The control of sway requires

integration of sensory information to detect and correct body position, and the amount of sway can be measured by the quantification of forces under the feet as continuous displacement of the center of pressure (Horak, 2009). Postural sway during stance are often modelled as an inverted pendulum biomechanical system were the center of mass is located at the upper end of the rigid body segment that pivots around one joint (i.e. ankle joint) at the base, although in the real world body sway includes control of multiple segments and joints. Convergent sensory information from the somatosensory (skin, muscle spindles, golgi tendon organ), vestibular (vestibular canals, otoliths) and visual system are integrated to control multiple segments and joints in locating the COM relative to base of support (Horak, 2009). One can decide at will what posture to assume (conscious motor act), at the same time the posture is controlled in an "automatic" way (unconscious motor act) by the sensory information available.

1.4 Muscle fatigue

Fatigue is an experience in daily life not easily quantified or measured, and in common language it is described as a feeling of weakness, decrement of performance or muscle pain (Roberto Merletti & Philip Parker, 2004). Fatigue itself is not a physical variable, and requires the definition of indexes based on physical variables that can be measured, such as force or torque during maximal voluntary contractions (MVC), or variables associated to the motor units (MUs) such as firing rates, conduction velocity and synchronisation, or variables associated to the EMG signal such as amplitude and spectral estimates from MUs or global estimates (Roberto Merletti & Philip Parker, 2004). In general muscle fatigue may develop at any level within the motor pathway from the cerebral cortex to the contractile elements within the muscle fibre, and depending on which side of the neuromuscular junction the limiting factor(s) are revealed, muscle fatigue may be classified as having central or peripheral origin (Enoka & Duchateau, 2008).

Activities in daily-life usually requires submaximal muscle activation, still muscle fatigue with central and peripheral origin may develop (Enoka & Duchateau, 2008; Gandevia, 2001). During submaximal prolonged contractions modifications within the neuromuscular system are observed, where increased descending motor drive recruits additional MUs or muscles in order to compensate for those that are fatiguing, and no decrement in task performance are observed (force may be maintained) while an increased sEMG signal are seen. Likewise, accumulation of metabolites during sustained muscle contractions may increase the afferent

feedback in e.g. group III and IV muscle afferent to spinal and supraspinal centers and reduce the voluntary drive (Gandevia, 2001; Sogaard, Gandevia, Todd, Petersen, & Taylor, 2006), and decreased force performance and reduced sEMG amplitude are observed during maximal voluntary contractions. Moreover, central muscle fatigue encompass cognitive factors like motivation, perception of the task and various avoidance behaviours (pain anticipation, pain avoidance, fear of pain, uncertainty) leading to reduced exertion and performance in voluntary activation (Al-Obaidi, Al-Zoabi, Al-Shuwaie, Al-Zaabie, & Nelson, 2003; Al-Obaidi, Nelson, Al-Awadhi, & Al-Shuwaie, 2000).

Peripheral or local muscle fatigue encompass ionic and metabolic changes at the muscle fibre level, where impaired action potential propagation (reduced conduction velocity) and exitatation-contraction coupling during a sustained muscle contraction are observed concomitant with reduced median frequency of the sEMG signals power spectrum (Roberto Merletti & Philip Parker, 2004; Semmler, Kutzscher, & Enoka, 1999).

1.6 Functional abnormalities in cLBP

Decreased back flexor- and extensor strength are observed in cLBP patients compared to HCs (Elfving, Dedering, & Németh, 2003; Nachemson & Lindh, 1969). Pain inhibition and expected pain increase are believed to be factors influencing trunk strength performance in cLBP (Al-Obaidi et al., 2000; Elfving et al., 2003). However, findings of similar strength performance indicate that the influence of trunk muscle strength may not be important in some cLBP sufferers (Balague, Damidot, Nordin, Parnianpour, & Waldburger, 1993; Nicolaisen & Jorgensen, 1985; Paalanne et al., 2008).

Increased fatigability in lumbar muscles (Kankaanpaa, Taimela, Laaksonen, Hanninen, & Airaksinen, 1998; Roy & Oddsson, 1998) is observed in cLBP patients compared to HCs. Observed changes in cLBP is widely thought to be the consequence of deconditioning due to disuse secondary to pain and pain related fear of physical activity and illness perception.

Absence of the flexion-relaxation phenomenon (FRP) with increased muscle activation in lumbar extensor muscles during full flexion is observed in cLBP (Geisser et al., 2004; Kaigle, Wessberg, & Hansson, 1998; Sihvonen, Partanen, Hanninen, & Soimakallio, 1991; Watson, Booker, Main, & Chen, 1997). Though often studied, the exact mechanism for FRP is not known. Proposed mechanisms include factors as muscle spasms and stretch reflex inhibition (Watson et al., 1997). One method reported for quantifying FRP over time or between individuals is the calculation of a flexion relaxation ratio (FRR) of the surface

electromyography amplitude (sEMG) of the trunk extensors during the trunk flexion phase to the sEMG amplitude recorded in full flexion (Sihvonen et al., 1991). The FRP may vary with movement speed (Sarti, Lison, Monfort, & Fuster, 2001), prolonged static flexion (Solomonow, Baratta, Banks, Freudenberger, & Zhou, 2003) and fatigue (Descarreaux, Lafond, Jeffrey-Gauthier, Centomo, & Cantin, 2008).

Impaired proprioception measured as reduced reposition accuracy is observed in cLBP compared to HCs (Brumagne, Cordo, Lysens, Verschueren, & Swinnen, 2000; K. L. Newcomer, Laskowski, Yu, Johnson, & An, 2000), although some studies report no difference (K. Newcomer, Laskowski, Yu, Larson, & An, 2000). Lumbar muscle fatigue seems to have effect on the ability to sense lumbar position and its change (Taimela, Kankaanpaa, & Luoto, 1999).

1.6.1 Muscle activity variability in cLBP

In chronic pain conditions, a reduced movement- (Lomond & Cote, 2010; Madeleine, 2010) and neuromuscular (Falla & Farina, 2008; Holtermann, Gronlund, Roeleveld, & Gerdle, 2011; Madeleine, 2010; G. L. Moseley & Hodges, 2006) variation is observed. Subjects in pain may have learned to avoid painful motor solutions hence more stereotypical solutions are preferred, even if they imply a less optimal performance (Cote, Raymond, Mathieu, Feldman, & Levin, 2005; Srinivasan & Mathiassen, 2012). Similar to pain, an association between motor variability and fatigue development is observed (Holtermann, Gronlund, Ingebrigtsen, Karlsson, & Roeleveld, 2010; van Dieen, Oude Vrielink, Housheer, Lotters, & Toussaint, 1993; van Dieen, Westebring-van der Putten, Kingma, & de Looze, 2009). Several motor control mechanisms are proposed to reduce the progressing fatigue during prolonged contractions. Such mechanisms may operate at single motor unit (MU) (i.e. muscle wisdom and doublet discharges (Bigland-Ritchie, Zijdewind, & Thomas, 2000)), between MUs (i.e. MU substitution (Bawa, Pang, Olesen, & Calancie, 2006)), between intramuscular regions (i.e. activity redistribution and differential activation (Dario Farina, Leclerc, Arendt-Nielsen, Buttelli, & Madeleine, 2008)) or between synergistic muscles (i.e. alternating activation (Holtermann & Roeleveld, 2006; Motoki Kouzaki & Shinohara, 2006)). Alternating muscle activity seems to have a direct impact on local blood flow (M. Kouzaki et al., 2003) and this type of muscle activation pattern has been suggested to prevent fatigue during sub-maximal contractions.

Differences in the neuromuscular activation of deep and superficial lumbar muscles are proposed (D. MacDonald, Moseley, & Hodges, 2009; D. A. MacDonald, Lorimer Moseley, & Hodges, 2006). However, in these studies the EMG activity from deep lumbar muscles was investigated with fine-wire electrodes, thus only small parts of the active muscle were recorded (R. Merletti & PA. Parker, 2004). Last decades, the introduction of large array- and high density surface EMG (HDsEMG) has made investigation of larger part of the muscles at interest accessible (D. Farina, Gazzoni, & Merletti, 2003; Roeleveld & Stegeman, 2002; Roeleveld, Stegeman, Vingerhoets, & van Oosterom, 1997). Applying a HDsEMG electrode grid over muscles at interest makes it possible to investigate deep and superficial muscles (Kleine, Schumann, Stegeman, & Scholle, 2000), spatial reorganization (Dario Farina et al., 2008; Tucker, Falla, Graven-Nielsen, & Farina, 2009) and amplitude distribution (Holtermann, Gronlund, Stefan Karlsson, & Roeleveld, 2008) of muscle activity during sustained isometric contractions.

1.6.2 Postural control and strategy in chronic low back pain

Postural control may be affected in cLBP and has frequently been investigated in assessing the amount of postural sway during shorter periods of standing (typically 60 s). Postural sway is usually examined by the excursion of the center of pressure (COP) on the supporting surface of a force plate. COP itself is not a true record of body sway, but rather a measure of how the motor system moves the COP (Ruhe, Fejer, & Walker, 2011). In this, different parts of the sensory systems may be involved.

Increased postural sway during quiet standing has been shown in cLBP patients (Mazaheri, Coenen, Parnianpour, Kiers, & van Dieen, 2013), although unchanged (Brumagne, Janssens, Knapen, Claeys, & Suuden-Johanson, 2008; della Volpe et al., 2006) and reduced postural sway (Mok, Brauer, & Hodges, 2004; Salavati et al., 2009) also have been reported. Different factors within the sensory-motor system have been attributed to decreased balance performance (or increased postural sway); deterioration in proprioceptive function and altered information from decreased performance of the sensory-motor system within lumbar structures is proposed to increase postural sway (Ruhe et al., 2011). Moreover, lumbar fatigue seems to impair the ability to sense a change in lumbar position (Madigan, Davidson, & Nussbaum, 2006; Taimela et al., 1999). Further, delayed reflex responses to perturbations have been shown in LBP patients (Radebold, Cholewicki, Polzhofer, & Greene, 2001) and delayed reflex responses may increase postural sway (Radebold et al., 2001). Muscle fatigue

seems in general to deteriorate the effectiveness of the sensory input and motor output of the postural system (Paillard, 2012). Further, pain inhibition is a mechanism suggested to contribute to increased sway, where nociceptive afferents may interfere with motor cortex and spinal motor-pathways (G. L. P. Moseley & Hodges, 2005; Ruhe et al., 2011). On the other hand, pain-related fear of movement may lead to a more rigid postural control strategy and reduced postural sway (Davis et al., 2011).

In contrast to quiet standing, few studies have examined postural control and strategy in cLBP during longer periods of standing. The nature of postural sway during prolonged standing differs from sway during quiet standing. While increased sway during quiet standing is interpreted as the amount of "noise" in the postural control system related to sensory sub-systems , large sway during prolonged standing reflects voluntary gross body movements performed to reduce perceived fatigue and musculoskeletal discomfort (Duarte & Zatsiorsky, 2000; Freitas, Wieczorek, Marchetti, & Duarte, 2005).

1.6.3 Gender differences

The prevalence of LBP is somewhat lower in women compared to men (Hoy et al., 2014). However, in Nordic populations, women is more likely to report LBP (Leboeuf-Yde, Nielsen, Kyvik, Fejer, & Hartvigsen, 2009) and are more absent from work and receive disability pension more frequently due to LBP (Hagen & Thune, 1998). Moreover, women show enhanced sensitivity to most forms of experimental pain (Fillingim, King, Ribeiro-Dasilva, Rahim-Williams, & Riley, 2009). Biological (i.e. hormonal) and psychosocial (i.e. gender role expectations) may be factors partly explaining why women are more afflicted by LBP (Fillingim et al., 2009; Leboeuf-Yde, Fejer, Nielsen, Kyvik, & Hartvigsen, 2011).

Lower muscular strength is observed in women compared to men (Larivière et al., 2006; Miller, MacDougall, Tarnopolsky, & Sale, 1993) and this seems primarily to be due to larger muscle fibres in men (Miller et al., 1993). Moreover, women have shown to be more fatigue resistant than males in submaximal contractions (Hicks, Kent-Braun, & Ditor, 2001; Larivière et al., 2006). Several factors may contribute to these observations. Women have in general a lower muscle mass and hence a lower absolute muscle forces are produced by women when performing the same relative work as men. Lower muscle force requires less muscle oxygen, exert less intramuscular pressure onto feed arteries and hence blood supply to active force producing muscles may be maintained (S. K. Hunter, 2014). Substrate utilization is another factor which may explain gender differences since women show greater capacity for lipid

metabolism to produce muscle energy and men utilize glycolytic pathways (Maher, Akhtar, Vockley, & Tarnopolsky, 2010; Roepstorff et al., 2006). Lipid metabolism in skeletal muscles of women is related to the presence of oestrogen (Maher, Akhtar, & Tarnopolsky, 2010). Moreover, in the erector spinae muscle, larger proportional area is occupied by the less fatigable type I muscle fibres in women (Mannion et al., 1997). Neuromuscular activation patterns may also contribute to observed differences in muscle fatigue, where women have increased alternating activation and enhanced muscle endurance (Larivière et al., 2006), although similar neuromuscular activations patterns have also been observed in women compared to men (Sandra K. Hunter & Enoka, 2003).

Worse performance in postural balance has been observed in women (Kim et al., 2010; Panzer, Bandinelli, & Hallett, 1995). However, observations of better (Era et al., 2006; Masui et al., 2005) and equal balance performance have also been reported in women (Bryant, Trew, Bruce, Kuisma, & Smith, 2005; Era, Heikkinen, Gause-Nilsson, & Schroll, 2002). Differences between studies in testing postures and balance task may partly explain the discrepant results (Kim et al., 2010).

2.0 Aims of the thesis

Alterations in postural control and reduced variability in trunk muscle activation are factors in the development and persistence of LBP (Descarreaux, Lalonde, & Normand, 2007; Geisser et al., 2004; Hodges & Tucker, 2011; Jacobs, Henry, & Nagle, 2009; D. MacDonald et al., 2009; G. L. Moseley & Hodges, 2006; van Dieën et al., 2003). The literature on postural control and motor variability during prolonged low level isometric muscle loads in cLBP is limited, and investigations of motor performance and strategies during daily life activities like sitting and standing may add to our understanding of why cLBP patients commonly are challenged by such.

The overall objective of this thesis is to gain insight in muscle functioning, postural strategies and fatigue in the lumbar region during low level isometric muscle contractions related to longer periods of sitting and standing in chronic low back pain (cLBP) patients compared to healthy control subjects (HCs).

The specific aim of paper I, II and III are:

I. To investigate electromyographic manifestations of fatigue in deep and superficial lumbar muscles during sustained sitting, whether such fatigue is associated with lumbar muscle variability between- (i.e. the alternating activation) or within sides (i.e. reduced temporal or spatial variation of the signal) and whether there are gender differences.

II. To investigate muscle activity variability in lumbar muscles within and between muscles on right and left side in cLBP patients compared to healthy control persons during sustained quiet sitting.

III. To investigate muscle activation level and variability in addition to postural control during 15 minutes of prolonged standing in cLBP patients compared to HCs and differences between cLBP patients and HCs in the effect of prolonged standing on neuromuscular control, proprioception, postural sway, strength, pain and perceived effort.

3.0 Methods

This thesis is based on two separate data collections. Both experiments were designed as cross-sectional experimental studies. In the first data collection, 18 patients (13 males and 5 females) and 32 HCs (16 male and 16 female) without back pain were included. Information from the lumbar muscle activation during sustained sitting was investigated with a high density surface EMG system (HDsEMG). In the second data collection, 17 patients (7male and 10 female) with cLBP and 21 HCs (8 female and 13 female) without back pain were included, and information from lumbar, abdominal and hip muscle activation were investigated during sustained standing with conventional bipolar EMG.

3.1 Participants

In both data collections cLBP patients were recruited from the outpatient clinic at Vestfold Hospital Trust - Kysthospitalet. Exclusion criteria for cLBP patients were anamnesis of medical or drug abuse, surgery on the musculoskeletal system of the trunk, known congenital malformation of the spine or scoliosis, systemic-neurological-degenerative disease, history of stroke, psychiatric disorder, pregnancy and abnormal blood pressure. Patients were asked not to use any medications except for Paracetamol or Ibuprofen preparations one week before examination and not to perform any back-straining exercises 48h prior to examination. In both studies the healthy controls were recruited from colleagues at the hospital, friends and relatives. Seven HCs participated in both studies. The exclusion criteria for the HCs were LBP in the previous year or LBP lasting more than a week in the previous 3 years. After inspection of the EMG signal from the first data collection during sustained sitting, seven HCs with subcutaneous soft tissue and fascia > 15 mm were excluded from data-analysis in due to poor signal quality. Therefore, 25 HCs were included in final analyses in paper I and II (13 males and 12 females). Characteristics of participants of both studies are presented in Table 1. One female HC was excluded from the analysis as she did not manage to complete the protocol due to dizziness from known low blood pressure.

Table 1. Mean (SD) of the participants characteristics in study samples I and II.

	Sustained quiet sitting study				Prolonged standing study			
	cLBP patients (n = 18)		HCs (n =25)		cLBP patients (n = 17)		HCs (n =20)	
Age (years)	39.9	(6.6)	40.8	(7.8)	39.0	(5.4)	40.2	(5.4)
Height (cm)	174.1	(9.6)	177.6	(7.9)	177.5	(6.5)	174.6	(8.9)
Weight (kg)	70.0	(12.1)	73.3	(9.6)	81.7	(15.7)	77.5	(16.7)
Gender (male/female)	13/5		13/12		7/10		8/12	
ODI (%)	26.9	(9.6)			21.1	(7.8)		
TSK	27.1	(7.4)			23.8	(8.6)		

ODI; Oswestry disability index, TSK; Tampa scale of kinesiophobia

All subjects signed an informed consent before inclusion. The project was approved by the Regional Committee for Medical Research Ethics (REK) in the South-Eastern Norwegian Regional Health Authority (S-08630a, 2008/1585 and 2012/1158/REK), and were conducted according to the Declaration of Helsinki.

3.2 Questionnaires

A custom-made questionnaire was utilized to collect the participants' characteristics. Oswestry Disability Index (ODI) was used to assess the LBP patient's disability level (Grotle, Brox, & Vollestad, 2003). Tampa Scale of Kinesiophibia was used to assess the LBP patient's level of fear of movement and/or (re)injury (Haugen, Grovle, Keller, & Grotle, 2008).

3.3 Experimental protocols

3.3.1 Sustained quiet sitting (paper I & II):

To control the sitting position 2 inclinometers were placed on the participants back; one located on the proc spinous in the lower part of the thoracic spine (Th12), and one on the sacrum at the S1-level. Target position (horizontal line with marked area of ± 1 degree on a total figure display of 10 degrees) and real time feedback (rising bar) of the inclinometer at Th12 was provided on an 19" computer screen placed at a distance of ~90 cm at eye level. Data from the inclinometers was collected with a sample rate of 1500 Hz and saved in a separate file during acquisition in MyoResearch XP Master Edition (Noraxon). HDsEMG was collected from lumbar muscles on both sides during the sitting.

To normalize sEMG, the subjects performed 3 isometric maximal voluntary contractions (MVC) of back extension against resistance of a strap around the upper part of the trunk while

sitting. After 10 minutes rest the participants were asked to maintain a target inclination of the trunk (5° forward inclination from vertical) for 30 minutes or until "task failure", defined as a deviation from the target inclination of ±1 degree for more than 3 s. During the sitting, subjects rated their perceived exertion (RPE) experienced every fifth minute on a scale ranging from 6-20 (Borg, 1982). Immediately after the sustained sitting a MVC was performed to estimate the amount of change in EMG voluntary activation after sitting. The experimenter gave verbal encouragement during all MVC trials.

3.3.2 Prolonged standing (paper III):

To measure angles of the trunk and pelvis two inclinometers were used. Conventional surface electromyography (sEMG) was recorded bilateral from m. erector spinae, m. rectus abdominis, m. external oblique and m. gluteus medius muscles. As a warm up procedure the participants walked 5 minutes at a treadmill at preferred speed before sensor placement, and walked across the room a couple times and performed 5 standing trunk flexions after sensor placement. The participants performed a prolonged standing trial and a set of pre and post prolonged standing tests; quiet standing trials, perceived pain and exertion ratings, flexion relaxation-, reposition- and maximal voluntary contraction tests. During all tests the participants wore socks. An overview of the data collection protocol is shown in Table 2, and the tests are described in more detail in the following paragraphs.

Table 2. Overview of the protocol sequence progression around the prolonged standing test with approximate duration (min)

Task	Duration (min)
Flexion Relaxation (FRR)	(1)
Reposition Error (RE)	(3)
Maximal Voluntary Contraction x3 (MVC)	(10)
Numeric Pain Rating Scale (NPRS)	(1)
Quiet Standing (with and without vision)	(1)
Prolonged Standing	(15)
Perceived Exertion Scale (RPE)	(1)
Quiet Standing Eyes Closed	(1)
Numeric Pain Rating Scale (NPRS)	(1)
Maximal Voluntary Contraction (MVC)	(2)
Flexion Relaxation (FRR)	(1)
Reposition Error (RE)	(3)

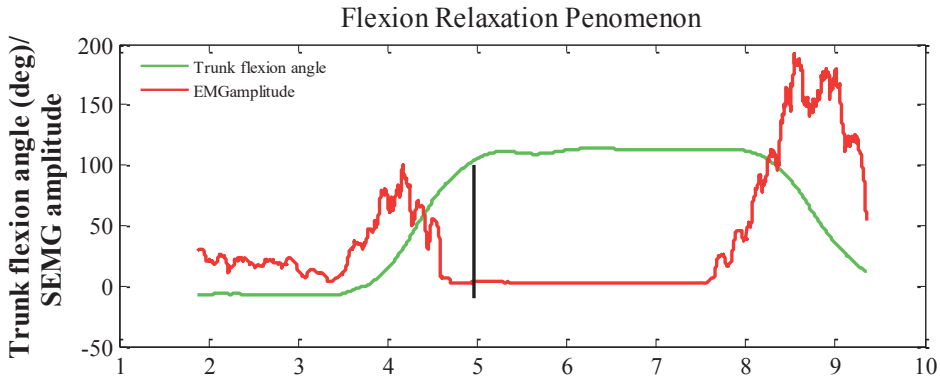
3.3.2.1 Quiet standing and prolonged standing

Quiet standing was performed with and without vision prior to and with vision immediately after the prolonged standing. During quiet standing the participants stood with one foot on each force plate for 60 seconds. The participants were instructed to stand with their feet approximately at pelvis width, look straight ahead and stand as still as possible with their arms in a comfortable position alongside their body.

Prolonged standing was performed while participants stood with one foot at each force plate while listening to two short fairy tales. The participants were not to leave the feet from the force plates and had to maintain an upright posture. They were not allowed to talk during the trial, but they were told to speak out clearly if they felt unwell or dizzy

3.3.2.2 Flexion relaxation ratio

The participants started standing for 5 s in an upright position immediately followed by a forward trunk flexion movement to the individual maximal trunk flexion position and returned to upright position after 3 s. This was repeated three consecutive times.



Figur 1. EMG from erector spina (ES) and trunk flexion angle. The vertical black line defines full flexion.

3.3.2.3 Reposition error

Reposition error was assessed by the ability to reproduce a target position of 30 degrees trunk flexion position while standing. The participants were instructed to stand in an upright neutral position, bend slowly forward and stop by the examiners command at 30 degrees of trunk flexion. The position was held for 10 seconds while the participants memorised the position. Participants returned to neutral position and were instructed to reproduce the target position as

accurately as they could. Participants reported to the tester when they felt the target position had been reached, after three seconds in the target position they returned to upright position. Target position was reproduced three times with a 10 second break between repetitions. The procedure was performed with and without vision.

3.3.2.4 Maximal voluntary contractions (paper I, II & III)

In paper I and II the subjects performed three isometric MVCs of back extension against resistance of a non-elastic polyester band around the upper part of the trunk (Th6-Th8 level) while sitting (vertical trunk position and 90° at the hip and knee joint). Each contraction lasted 5 s with 3 minutes rest between. A break of 10 minutes was given to the participants between MVC and the performance of the sustained quiet sitting task. Immediately after the sustained sitting an additional MVC was performed to estimate the amount of change in voluntary activation after sitting.

In paper III the subjects performed three isometric MVCs in back extension followed by three in abdominal trunk flexion with one minute break between the contractions. Isometric MVCs was held for ~3 s with 1 min rest between. All MVCs in paper III were performed in a standing position in a modified "Cybex 6000 back extension module" which gave support at front/back of pelvis during testing. A force sensor (Inline Force Sensor (0-2224 N) Noraxon U.S.A. Inc.) attached horizontally to the wall and a non-elastic polyester band around the subjects torso at Th6-Th8 level was used to measure the force during MVC.

The experimenter gave verbal encouragement during all MVC trials.

3.4 Recordings and analyses

3.4.1 High density surface EMG recordings (paper I & II)

Ultrasound measurements were taken of the distance (mm) between the skin and the paraspinal muscles (subcutaneous soft tissue and fascia) 3 cm lateral of the spinous process at the L3-L4 level. Muscle activation in lumbar muscles was recorded with two HDsEMG grids consisting of 9 by 13 Ag-AgCl electrodes. The grid covers 3.2 X 5.2 mm of the skin surface with 1.5 mm electrode diameter and 4 mm inter electrode distance. The sEMG data was collected from all electrodes by two *Active two* amplifier systems (BioSemi, Amsterdam, The Netherlands) in a daisy-chain configuration with a sampling rate of 2048 Hz, where each electrode grid had a common reference (monopolar recording). The data-acquisition was done

with the MyoDaq-software developed at the Department of Clinical Neurophysiology of the Radboud University Nijmegen Medical Center. The electrode-grids were located on the lower part of the lumbar musculature with one grid on each side of the lumbar spine. The base of the grids was at the level of spina iliaca posterior superior and 3 cm from the spine process to the midpoint of the grids (Figure 1.). The skin was cleaned with alcohol and prepared with an abrasive paste before double sided tape was attached to the skin. Electrode gel was applied before the electrode grids were attached to the tape.

3.4.2 High density surface EMG analyses (paper I & II)

The monopolar HDsEMG signals were band pass filtered at 30 – 300Hz. The quality of the monopolar EMG signals was determined by visual inspection and channels with poor signal quality were removed. Next the EMG signal was bipolar spatial filtered in the cranial-caudal direction (12 mm IED), leaving 99 bipolar EMG signals in 9 columns and 11 rows for each grid. For each monopolar and bipolar signal (in paper I) or just for each bipolar signal (for paper 2) the root mean square (RMS) values was calculated in 1 s non-overlapping time-windows and normalized to the 1 s highest RMS value (RMSmax) during the three MVCs in sitting trunk extension performed prior to the sustained sitting. To assess the level of local muscle fatigue during sitting, the median frequency (MDF) of the power density spectrum was computed in epochs of 1 s.

For each grid and all epochs, the overall average RMS EMG amplitude was obtained. Changes in grid average RMS and MDF during the sustained quiet sitting were quantified as the slope of a linear regression (RMSslope and MDFslope).

Information of the relative activity between lumbar muscles on left and right side of the lumbar spine was attained from the average RMS from the HDsEMG grids. The temporal trend was removed from both grid RMS signal and normalized to the second highest value (to avoid normalizing to artifacts) in each RMS signal of the contraction. The relative difference between the RMS signals was quantified and the frequency of alternating activation with relative difference above 30 % was calculated.

To investigate temporal variations in amplitude, the grid averaged signals were de-trended and the temporal coefficient of variation (COV) for each grid was calculated (COV =100*SD de-trended RMS /mean RMS). Changes in RMS distribution in each grid was quantified by calculating correlation coefficients (CCT) between RMS amplitudes of all electrodes within the grid at one epoch with the RMS values of the same electrodes or electrode pair at another

epoch (Holtermann, Roeleveld, & Karlsson, 2005). The median value of correlation coefficients from each grid gives quantitative information about the extent of change in spatial distribution within the grid. A low correlation indicates a large change in RMS distribution during the contraction. A coefficient of variation of all correlations (CCT_{COV} = 100*SD CCT/mean CCT) was calculated, providing information of the temporal variability of the RMS distribution, where a high coefficient of variation indicates a large variation in RMS distribution change during the sitting.

In paper II the spatial variability of the EMG amplitudes within the electrode grid during the quiet sitting was investigated by calculation of the coefficient of variation of all RMS signals in the grid during quiet sitting ($COV_{SPATIAL}$ =100*SD detrended RMS /mean RMS). The standard deviation of the detrended RMS from each bipolar signal was divided on the average RMS from each individual bipolar EMG. Low $COV_{SPATIAL}$ indicates large variability in RMS within the electrode grid during the sitting.

There were no significant differences in any variables calculated from sEMG data collected from the left or right side lumbar muscles. To reduce data, all EMG parameters were averaged bilaterally.

3.4.3 sEMG recordings and analyses (paper III)

Waist-hip ratio was measured as waist circumference/hip circumference. Muscle activity from erector spina (L5, 3cm from midline) , gluteus medius (50% on the line from the crista iliaca to the greater trochanter), rectus abdominus (1 cm above umbilicus and 2 cm lateral to midline) and external oblique (lateral to the Rectus abdominis m. and directly above the anterior superior iliac spine, halfway between the crest and the ribs at a slightly oblique angle so that they run parallel to the muscle fibres) was recorded bilaterally with pairs (20 mm IED) of disposable sEMG electrodes (Ambu Blue Sensor M-00-S/50). Reference electrode was placed on S1 level. The skin at the electrode sites was shaved and abraded with alcohol before the bipolar sEMG electrodes were placed aligned with the muscle fibre direction. The sEMG signals were collected with a 1500 Hz sampling frequency (Noraxon TeleMyo 2400, U.S.A Inc). The sEMG data were low pass filtered with an 8^{th}-order recursive Butterworth filter of 500 Hz. A 40 Hz high-pass filter was used to remove artefacts from electrocardiography and movement. For each EMG signal during FRR, MVC and quiet/prolonged standing the root mean square (RMS) was calculated in windows of 100 ms, 500 ms and 1 s respectively, and signals from the standing tests were normalized to the highest RMS value during the three

MVCs performed prior to standing. In addition, median frequency (MDF) of the power density spectrum was computed in epochs of 1 s during prolonged standing.
Flexion relaxation ratios were calculated as the ratio between the maximum RMS value during forward flexion movement divided on the minimum RMS value during maximal flexion (Geisser et al., 2004; Watson et al., 1997).

3.4.4 Force recordings and analyses (paper III)

Ground reaction forces and moments in x- (medio-lateral), y- (anterior-posterior), and z- (vertical) direction were measured for each foot separately during quiet- and prolonged standing using two AMTI force plates (Advanced Mechanical Technology Inc., MA, USA; model BP400600-1000, 60 cm x 40 cm).
Force sensor data were collected with TeleMyo 2400 (Noraxon Inc., USA). Prior to digitalization, all channels were filtered with an 8^{th}-order Butterworth low-pas filter (500Hz). Analogue output from the Noraxon system was synchronised with force plate data and stored in Qualisys Track Manager (Qualisys Medical AB, Sweden, version 2.7) and exported to Matlab R2011a (The Mathworks Inc., USA) for post processing and analyses. All force data were sampled with 1500 Hz.
Force data were low pass filtered with an 8^{th}-order recursive Butterworth filter of 20 Hz.
In the first second of each MVC trial there where was no force applied to the force sensor except from the attached strap. The force data from this epoch was used to calculate the force offset. From the maximal voluntary contractions the trunk flexion and extension strength was determined as the highest force produced during the three MVC repetitions before and to the single repetition after the standing. Force was normalized to body weight (N/kg).
The first second of each quiet and prolonged standing trial the force plates was unloaded, and the ground reaction force data from this epoch was used to calculate the ground reaction force offset. From the quiet standing trials data from the last 50 seconds were analysed. From the prolonged standing, the first 10 seconds of data were removed. Centre of pressure (COP) was calculated from the ground reaction forces and moments. Data from the two force plates were combined to calculate global COP for the following three measures that were used to summarize COP displacement: RMS distance from mean COP (COP RMS) and COP speed, in both anterior-posterior (A-P) and medial-lateral (M-L) directions separately, and the area of COP displacement (COP area) (Freitas et al., 2005; Lafond et al., 2009). COP speed was defined as overall COP displacement (length of the COP trace) divided by the total time

period. COP area was calculated using the principal component analysis (Oliveira, Simpson, & Nadal, 1996). The principal component analysis calculates an ellipse that fits the data. The COP area corresponds to the area of the ellipse, where the data samples lie inside with 95% confidence interval.

The number of body weight shifts during prolonged standing was calculated from the two individual force plates. A body weight shifts was defined as a change from symmetrical stance with 50 % body weight on each leg, to asymmetrical stance with more than 65 % body weight on one leg and vice versa (Gallagher, Nelson-Wong, & Callaghan, 2011).

3.4.5 Trunk angels and analyses (paper I, II & III)

The analogue angular data at 1500 Hz was attained from the inclinometers. The angular data was low pass filtered and divided in time epochs of 1 s. In paper I and II two 2D inclinometers (Noraxon U.S.A Inc) were used to standardize the sitting position and to measure changes and variability during sitting in trunk and pelvis position. The inclinometers were placed on the skin at the level of Th 12 and one at S1. Target position during sustained quiet sitting was set to 5° trunk inclination from vertical (horizontal line with marked area of ±1 degree on a total figure display of 10 degrees) and real time feedback (rising bar) from inclinometer at Th 12 was provided at a 19" computer screen.

The absolute change in trunk and pelvis position was calculated as the average of the medial-lateral and anterior-posterior position during the last minute of contraction (sitting) minus the average position during the first minute. The variability of the trunk and pelvis position during sitting was investigated by the standard deviation (SD) of the medial-lateral and anterior-posterior position from the inclinometer data.

In paper III the two inclinometers were used to measure trunk angles in the sagittal plane in the reposition error test and during the flexion relaxation test. The reposition mean error was calculated as the absolute difference between the actual target position and the mean of the three replicated positions, ignoring the direction of the error.

3.4.6 Low back pain and perceived exertion (paper I, II & III)

The subjects rated the level of perceived low back pain (LBP) on a numeric pain rating scale (NPRS) ranging from 0 (no pain) to 10 (worst imaginable pain). LBP was rated before and after the sustained sitting and prolonged standing.

The Borg scale (Borg, 1990) was used to assess the level of perceived exertion (RPE) during and after the sustained sitting (paper I and II) and after the prolonged standing (paper III). The scale ranges from 6 (no exertion) to 20 (maximal exertion).

3.5 Statistics

Inn all papers a Shapiro-Wilk W-test for normality was performed on all dependent variables before statistical analysis. Parametric statistics were applied on normal distributed variables, while non-parametric alternatives were used for non-normal distributed variables. Nonparametric statistics were also used if the measures had non-homogeneity of variances, tested by the Levene's test. Paired statistics (Wilcoxon Signed Rank Tests and Paired Samples T-Tests) were applied to investigate the change in variables from before to after sustained sitting and prolonged standing. The slopes for MDF and RMS were tested against zero. Differences between men and women in paper I and between cLBP patients and HCs in paper II and II were evaluated by independent samples tests. In paper I correlations were obtained between measures of variability (CCTMED, CCTCOV and COV) and slopes of RMS, MDF and RPE. The significance level was set to $P < 0.05$, a trend to $P<0.1$. Comparisons were performed two tailed.

4.0 Main results

Paper I: Alternating activation is related to fatigue in lumbar muscles during sustained sitting.

The aim of this paper was to investigate whether muscle fatigue in deep (mostly reflected in monopolar EMG) and superficial lumbar muscles (mostly reflected in bipolar EMG) occur during 30 minutes of quiet sitting and whether fatigue in lumbar muscles is associated with variability in lumbar muscle activity between or within sides, and whether there are gender differences. The activation level in lumbar muscles at the start of the sitting was on average 18 and 11 % RMSmax in bipolar and monopolar EMG respectively, without any gender difference. The relative activation level in lumbar muscles was significant higher in bipolar RMS (%RMSmax) ($p < 0.01$) and higher values of bipolar MDF (Hz) ($p < 0.01$) compared to monopolar. During the sitting the mono- and bipolar RMS slightly increased ($p<0.01$) while MDF remained unchanged. The average ratings of subjective perceived exertion (RPE) increased from 6 to 13 on a scale ranging from 6 to 21, without gender differences. The alternating activation between left and right side of lumbar muscles was similar in bipolar and monopolar EMG (8.5 min^{-1} and 8.0 min^{-1} respectively) without gender difference. Alternating activation was associated with fatigue development, where higher frequencies of alternating activation was correlated with increased perceived exertions ($p = 0.03$) and a trend to correlate with decreased MDF ($p = 0.05$). A similar tendency was seen between increased spatial and temporal variability and less decreased MDF and less increased RPE. Further there was no gender effect on changes in MDF, RPE, RMS or variability measures. In conclusion there was no direct sign of muscle fatigue in the EMG signal since MDF stayed unchanged during the sustained quiet sitting. However, the increase in EMG amplitude indicates additional motor unit recruitment as a compensation for muscle fatigue and the subjects clearly indicated a subjective feeling of fatigue. The alternating activation between sides of lumbar muscles was related to fatigue development and a similar tendency was observed between increased temporal and spatial variability and decreased MDF and increased RPE. There was no gender effect on changes in MDF, RPE, RMS or variability measures.

Paper II: Lumbar muscle activation and variability during sustained quiet sitting in chronic low back pain patients.

The purpose of this paper was to investigate if variability in muscle activity in lumbar muscle activation is different in cLBP patients compared to healthy control subjects (HCs) during sustained quiet sitting. Only very small changes in the sitting position were observed during the sitting (all changes < 2.1° for trunk and pelvis position), although a more variable sitting position was observed in cLBP patients compared to HCs, significant in all directions ($p < 0.05$) except for the anterior-posterior direction of the pelvis ($p = 0.25$). At the start of the sitting the muscle activity level was lower in absolute RMS amplitude (uV) in the cLBP patients compared to HCs ($p < 0.01$), while the muscle activity level in RMS normalized to the activation level obtained during MVC (%RMSmvc) had a tendency to be higher in cLBP patients ($p=0.06$). In addition, the MDF was higher in cLBP patients at the start of the sitting ($p<0.01$). During the sitting both the absolute and relative muscle activity level increased significantly in both groups ($p<0.01$) while the MDF remained unchanged. There were no group differences in the change in muscle activation level or MDF during the sitting. Compared to HCs, cLBP patients had lower temporal variation in the muscle activity ($p<0.03$). Alternating activation was observed in cLBP patients and in HCs, without a group difference ($p = 0.56$). The spatial variability of the EMG amplitudes within the electrode grids during the sitting ($COV_{SPATIAL}$) and the EMG spatio-temporal correlation (CCT_{MED}) were high without group differences ($COV_{SPATIAL}$; $p = 0.46$, CCT_{MED}; $p = 0.56$).
Chronic LBP patients reported higher RPE at start and after the sitting and had a greater change in the RPE after the sitting compared to HCs (all p-values ≤ 0.02). Moreover, cLBP patients reported more LBP before ($p < 0.01$) and after the sitting ($p < 0.01$), and the change in pain after sitting was significant in cLBP patients ($p = 0.01$). On average cLBP patients ended the sitting earlier compared to HCs ($p < 0.01$). In conclusion, despite a higher activation level and reduced temporal variation in activation and possibly due to increased movement variation and similar spatial activation variation, no differences in muscle fatigue during sitting could be detected between cLPB patients and HCs. Moreover, cLBP patients had increased perceived exertion and LBP both at the start and as a result of sitting and several of those patients ended the sitting prematurely due to this.

Paper III: Postural strategy and trunk muscle activation during prolonged standing in chronic low back pain patients.

The purpose of this paper was to investigate if cLBP patients have a different postural control and strategy during a period of prolonged standing, and whether cLBP patients are more affected by prolonged standing. Chronic low back patients had a more variable standing position where they on average performed significantly more body weight shifts ($p = 0.03$) and had increased postural sway values during the standing compared to healthy control subjects (HCs). Further, cLBP patients had relatively higher trunk muscle activation level (% RMSmax) at start and during the prolonged standing. Neither cLBP patients nor HC showed signs of muscle fatigue in the EMG signals during standing (no decrease in MDF or increase in RMS). The temporal variability in muscle activity was high in gluteus medius and erector spina muscles and low in rectus abdominus, without any group differences ($p \geq 0.09$). Postural sway during quiet standing (60 s) before and after the prolonged standing was not different in cLPB patients ($p \geq 0.11$) and there were no group differences in changes. Lower trunk extension- and flexion strength was observed in cLBP patients before and after the prolonged standing ($p \leq 0.05$), and both group had significant reduction in strength after standing ($p \leq 0.01$), although not significant different between groups ($p \geq 0.11$). The FRR was on average lower in cLBP patients both before and after the standing ($p \leq 0.01$). There was a significant reduction in FRR in both groups, although the relative change in FRR was similar in cLBP patients and HCs ($p \geq 0.64$). There were no significant differences between groups or pre to post changes in any of the RE variables or tests. The subjective perceived exertion of the standing was higher ($p \leq 0.01$) after the standing, and the change in pain perception from pre to post was greater ($p \leq 0.01$) in cLBP patients. In conclusion cLBP patients present a normal postural strategy during prolonged standing with increased movement variability due to increased perception of musculoskeletal discomfort and pain, and cLBP patients don't seem more affected by prolonged standing than HCs.

5.0 Discussion

The overall objective of this thesis was to gain insight in muscle functioning, postural strategies and fatigue in the lumbar region during low level isometric muscle contractions related to longer periods of sitting and standing in chronic low back pain (cLBP) patients compared to healthy control subjects (HCs).

Prolonged sitting and standing increased the RPE in HCs and cLBP patients, with higher initial levels of RPE and larger increase in RPE in cLBP patients. This subjective indicator of fatigue was only partly accompanied by signs of local fatigue in the EMG signal. The MDF of the EMG signal did not show a general sign of local muscle fatigue during sustained quiet sitting (paper I & II) nor during prolonged standing (paper III) and a significant increase in muscle activation (EMG amplitude) was only observed during sitting (paper I & II), but during standing (paper III) no significant change in EMG RMS was observed. These unchanged MDF and increased RMS during sitting are believed to be a result of recruitment of bigger and faster MUs in order to compensate for those that are fatiguing, and findings during sitting adds to similar results during long duration contractions at low force (D. Farina et al., 2003; van Dieen, Heijblom, & Bunkens, 1998). Possibly due to the relatively low muscle activation level (19-25 %RMSmvc in sitting versus 7-12 %RMSmvc in standing) and the rather high muscle activation variability (COV 7-8% in sitting versus 26-34% in standing) in lumbar muscles, no sign of muscle fatigue could be observed during standing (paper III). Relatively higher muscle activation level was seen in cLBP patients already at start of the sitting (~25 %RMSmvc) and standing (~12 %RMSmvc). Augmented muscle activation is observed when anticipating pain (Hodges, Tsao, & Sims, 2015; G. L. Moseley, Nicholas, & Hodges, 2004). No information of anticipation of pain was collected from the cLBP patients during sitting or standing in papers II and III. Moreover, the absence of a specific cause to LBP may create an uncertainty of what LBP represents, thus the increased muscle activation could be a way to increase the "safety margin" for postural control.

In the following discussion, muscle functioning and fatigue during sitting and standing will be addressed first followed by postural control and strategy during prolonged standing. Thereafter methodological considerations of measurements and analysis are addressed before a conclusion of the contribution of the findings of the thesis.

5.1 Muscle functioning and fatigue

Alternating activation between sides

Higher frequencies of alternating activation between both sides of lumbar muscles were found to be related to muscle fatigue as indicated by a correlation between a decrease in MDF of the EMG signal and an increase in RPE in healthy pain-free subjects (paper I). Increased fatigability has been observed in cLBP patients (Kankaanpaa, Taimela, et al., 1998), thus a different alternating activation in patients could be expected. However, cLBP patients and HCs had similar alternating activation and similar changes in EMG during sitting, indicating a similar local muscle fatigue development during sitting (paper II). Results from paper I and II are in line with observations in previous studies where low frequency of differential activation between biceps brachii muscle compartments is related to decreased fatigue development (Holtermann et al., 2010). Moreover, observations of increased rating of RPE and pain in cLBP patients compared to HCs during sitting with similar alternating activity indicate that central aspects of fatigue and pain may not be factors mediating alternating activation or be affected by it.

Afferent feedback from local muscle fatigue via interneurons to α-motoneurons has been suggested as a mechanism for alternating activation between muscles to occur in low level contractions (Motoki Kouzaki & Shinohara, 2006). Rather long duration of alternating activations (30 – 60 s) may be needed in order to subsequently influence local blood circulation (M. Kouzaki et al., 2003), and the high frequency (i.e. short duration) of alternating activity in paper I and II might have been of too short duration to have influence on factors (e.g. local blood circulation) determining local muscle fatigue during sustained sitting. The force level of the contraction can be a factor influencing the frequency of alternating activation (Holtermann et al., 2010; Motoki Kouzaki & Shinohara, 2006) where lower force levels on the contraction seems required in order to observe the longer durations of alternating activity needed to influence local blood circulation. Hence, the absence of low frequency alternating activation at the moderate contraction level during sitting (around 20 %RMSmvc) may be due to the high cost to sustain an activation difference in lumbar muscles between sides. However, this "cost" was not higher in cLBP patients since similar increase in RMS during and reduced RMS in MVC after sitting was observed and similar alternating activation. Investigation of alternating activity in lumbar muscles at lower contraction levels may therefore reveal lower frequencies of alternating activity and would be an interesting theme for future studies.

Temporal and spatial variation of activation of the lumbar muscles

The temporal variability in lumbar muscle activation was lower in cLBP patients compared to HCs during the sitting (paper II) while similar variability in muscle activation was observed during prolonged standing (paper III). The redundant muscular system surrounding the lumbar spine enables different parts of the lumbar muscles to be activated in order to maintain daily- activities as sitting and standing. Thus, load-sharing muscle activity was expected to be observed as increased variability in muscle activation is known to prevent a potential (mechanical) overload of muscle fibres and/or parts of the muscles. Despite increased variation in sitting- (paper II) and standing posture (paper III) in cLBP patients, no increased muscle activation variability was observed. However, cLBP patients had relatively higher muscle activation already at start, indicating a reduced ability to relax muscles. Likely due to increased movement variability during standing (paper III), cLBP patients could compensate for the relatively high muscle activation level, resulting in a similar to HCs muscle activation variability. Presumably this also kept the musculoskeletal pain and discomfort at a tolerable level during prolonged standing (discussed in section 5.3). The observation of reduced temporal variability in muscle activity in cLBP during the sitting task (paper II) is in line with reduced motor variability in cLBP and linked to muscle fatigue (Abboud et al., 2014). Moreover, reduced temporal variability has been shown to cause electromyographic manifestations of fatigue during low level activity of trunk muscles (van Dieen et al., 2009). However, the MDF of the EMG signal did not show a general sign of local muscle fatigue during sitting (paper I and II) nor during standing (paper III). These unchanged MDF and increased RMS during sitting in paper I & II adds to similar results during long duration contractions at low force (D. Farina et al., 2003; van Dieen et al., 1998).

Reduced spatial variability in the RMS distribution has been observed in cLBP (Abboud et al., 2014; Falla, Gizzi, Tschapek, Erlenwein, & Petzke, 2014). During sitting (paper II) both cLBP patients and HCs had little change in the RMS distribution (high CCT_{MED}; around 0.9) and low variability in RMS within the grid (high $COV_{SPATIAL}$; around 27). However, differences in experimental protocols, where relatively higher muscle contraction levels were applied in Abboud et al. study (40-50 % MVC force versus ca 20 %RMSmax in paper I and II) and a dynamic repetitive task was applied in Falla et al.'s study makes it difficult to compare the results from the quiet sitting in paper II.

Maximal voluntary contractions

Low maximal RMS (paper II and unpublished results related to paper III) was observed in cLBP patients during the MVC before sitting and standing, and low absolute RMS at the start of the sitting (paper II), however, high absolute RMS was observed in lumbar muscles at start of the standing (unpublished results related to paper III). Reduced RMS amplitude indicates a reduced voluntary drive in cLBP patients. Pain inhibition by nociceptive signals via afferents to α-motoneurons may occur at the spinal level (van Dieën et al., 2003), and experimental pain has shown to reduce cortical excitability on the supraspinal level (Le Pera et al., 2001). Thus, it is likely that pain perceived by the patients may have influenced voluntary activation on several levels within the motor pathway. Moreover, anticipation of aggravation of the LBP when performing MVC may have influenced the patient's motivation and possibly lead to a pain avoidance behaviour and reduced voluntary drive (D. Farina, Arendt-Nielsen, & Graven-Nielsen, 2005).

Low RMS EMG during MVC may bias the normalised RMS EMG (%EMGmvc) towards an elevated activation level during sitting and standing, and consequently this would be interpreted as increased muscle load. During sitting, and after standing, cLBP patients did report higher RPE indicating higher muscle load experience in cLBP patients. Moreover, higher absolute RMS was found in lumbar muscles in cLBP patients during standing. Thus, the relative muscle activity level is more representative of the subjective experience reported by participants in this thesis.

Gender effect

Women have shown to be more fatigue resistant compared to men in sustained contractions (Hicks et al., 2001; Larivière et al., 2006). No effect of gender on fatigue indicators as MDF, RPE RMS or in any muscle activation variability measures was found in paper I. The majority of studies showing less fatigable back muscles in women compared to men used the Biering-Sorensen test were the load (40-60 % force MVC (Callaghan, Gunning, & McGill, 1998; Dedering, Nemeth, & Harms-Ringdahl, 1999)) involves the mass of the trunk (Kankaanpaa, Laaksonen, et al., 1998; Mannion & Dolan, 1994). Thus, less fatigability in women may be explained from the possibility of a gender differences in the relative load induced by lower trunk mass in women. Lower muscle force requires less muscle oxygen, exert less intramuscular pressure onto feed arteries and hence blood supply to active force producing muscles may be maintained and hence less muscle fatigue (S. K. Hunter, 2014). The sitting

position with 5° trunk inclination presumably requires lower contraction level in lumbar muscles (<20 %RMSmax) than the Biering-Sorensen test possibly minimizing the effect of gender differences in trunk mass on lumbar muscle fatigue. However, a gender effect was observed in bipolar EMG during the sitting where men had more increase in RMS during the sitting, indicating that men recruited bigger and faster motor units to maintain sitting, possibly reflecting of higher trunk mass in men compared to women in paper II. In addition, men had a slightly larger change in the anterior - posterior pelvis position during sitting which may contribute to the larger increase in RMS.

5.2 Postural strategy

Compared to HCs the cLBP patients had increased variability in the sitting position (paper II), more body weight shifts and increased body sway during, and similar change in balance performance after standing (paper III). These observations oppose a previous observation during prolonged standing (Lafond et al., 2009) showing a postural strategy with reduced movement during prolonged standing possibly contributing to their LBP, and reduced balance performance after interpreted as a neuromuscular indication of fatigue or discomfort. Although no apparent differences in study population or instructions given during our standing task compared to the study of Lafond et al. can explain the differing results, the information cLBP patients received during the clinical examination performed at the outpatient clinic during the recruitment process may have contributed. Here cLBP patients get the message that the spine is strong and will not easily suffer any injury with normal use, it is beneficial to be physical active and that less pain focus might facilitate natural and less painful movements. This information may have encouraged cLBP patients to a variable postural strategy during standing as a response to increased perception of musculoskeletal discomfort and pain while standing. Then, the increased variability during sitting and standing could be a response of higher RPE and more musculoskeletal discomfort and pain reported by cLBP patients (Duarte & Zatsiorsky, 2000; Lafond et al., 2009).

Despite increased variation in sitting (paper II) and standing (paper III) no increased variation in muscle activation was observed. This supports the theory that cLBP patients may have difficult to relax muscles despite changing position, and may result in a constant low-level muscle activation which may result in local muscle fatigue and potential the development or maintenance of musculoskeletal pain. Reduced ability to relax muscles after activation and

shorter rest periods has been observed in neck pain patients (Falla & Farina, 2008; Ostensvik, Veiersted, & Nilsen, 2009; Veiersted, Westgaard, & Andersen, 1993).

RPE has been related to central fatigue development during sustained low-force contractions (Sogaard et al., 2006; van Dieen et al., 2009), and findings of high RPE in cLBP patients at start of sitting (paper II), and similar to cLBP patients performance in trunk extension/flexion strength and FRR in HCs after standing (paper III) may indicate that cLBP patients already at start of the sitting and standing were influenced by static muscle activation.

Eleven out of 18 cLBP patients prematurely ended the sitting protocol in paper II, while all patients managed to endure the prolonged standing protocol in paper III. The constraint sitting position limited the participants in changing sitting position, which lead to very high RPE in cLBP patients (19 on Borg (6-20)) and a significant increase in LBP. Plausibly this made the cLBP patients to end the sitting task. On the other hand, the unconstraint nature of the standing task allowed the subjects to freely change standing posture, which resulted in moderate level of RPE in cLBP patients (13.5) and a tolerable increase in pain (1.5 on the NPRS). These results are in agreement with other studies (Dunk & Callaghan, 2010; Nairn, Azar, & Drake, 2013) and support the presence of reduced tolerance for low-level static muscle load induced by sitting and standing in cLBP patients.

5.2.1 Effect of prolonged standing (paper III)

Trunk flexion and extension strength and FRR were reduced and postural sway was to some degree increased after prolonged standing in both cLBP patients and HCs, without any group differences in the changes. This indicates fatigue development during prolonged standing, although no sign of local muscle fatigue in the EMG signal was observed, and is in line with observations of fatigue being a factor modifying the flexion relaxation phenomenon (Descarreaux, Lafond, & Cantin, 2010) and postural sway (Davidson, Madigan, & Nussbaum, 2004; Madigan et al., 2006; Wilson, Madigan, Davidson, & Nussbaum, 2006).

No difference between cLBP patients and HCs in the measure of reposition error or in its change after prolonged standing was found. Fatigue has shown to impair reposition of the trunk in both cLBP patients and healthy subjects (Taimela et al., 1999). Altered proprioceptive function has been associated with LBP in some studies (Brumagne et al., 2000) while no association has been found in others (Asell, Sjolander, Kerschbaumer, & Djupsjobacka, 2006; K. Newcomer et al., 2000). Similar fatigue development during standing in cLBP patients compared to HCs in paper III may partly explain the result. Reduced

proprioceptive function has been argued to cause the reduced balance and stiff behaviour in cLBP patients (Lafond et al., 2009). Results from this thesis do not support this.

5.3 Measurement & analysis considerations

The EMG signal collected at the skin surface is generated by the electrical activity of the muscle fibres active during a contraction. The number of active MUs (increased numbers of active MUs generates larger EMG signal), their size (bigger MUs generates larger EMG signal) and the distance from at the recording electrode are factors which have influence on the amplitude of the collected EMG signal (Roberto Merletti & Philip Parker, 2004). With regard to the distance the EMG signal must travel from generation to detection, the amount of subcutaneous fat is an important factor. The distance from active muscle fibres to the skin surface was in paper I and II measured by ultra sound. As an indication of the amount of subcutaneous fat tissue, measures of body composition like body mass index and waist-hip ratio are frequently used. In this thesis there was no difference between men and women or between cLBP patients and HCs in any of these measures. In order to minimize any potentially impact these factors could have when comparing sEMG activity between subjects in this thesis, the sEMG signal was normalized to maximal RMS amplitude (EMGmax) recorded during the MVC contraction performed before sitting (paper I and II) and standing (paper III). However, when comparing sEMG activity between subjects with and without pain, normalization to EMGmax is of concern. During maximal voluntary contractions it may be expected that patients experiencing pain would produce less force in order to avoid pain. Consequently this may result in higher normalized sEMG activity patterns (%RMS_{MVC}) in cLBP patients. In paper II cLBP patients had lower RMS_{MVC} performance in back extensor muscles and in paper III lower strength performance were observed in cLBP patients compared to HCs during MVC performed before the prolonged standing. However, several conclusions in this thesis are based upon temporal and spatial variability of muscle activation, not influenced by the relative sEMG activation level, and the change in strength after standing in paper III was not different in cLBP patient compared to HCs, indicating that reduced performance in patients during MVC might not solely be as a result of pain avoidance behaviour.

Temporal spatial variation in RMS distribution

The HDsEMG technique utilized in paper I and II in this thesis provides a measure of the distribution of the RMS amplitudes from a relative large area of the lumbar muscles. The

method enables a non-invasive investigation of intra muscular activation and control large fraction of the lumbar muscles (Holtermann & Roeleveld, 2006). The numerous lumbar muscles provide a pool of possible motor solutions that may be recruited in order to maintain the sitting position in paper I and II. Motor unit recruitment or a shift in active muscles to compensate for muscle fatigue development during the sitting was expected to occur during sitting. Both recruitment of additional MUs and a shift in active muscles would change the RMS distribution recorded by the HDsEMG grid. Changes of the distribution of RMS amplitude during sustained contractions has been observed during submaximal sustained constant force contractions and related to motor unit recruitment in upper trapezius muscle (Holtermann & Roeleveld, 2006), and to reflect modulation of activity between muscles of the erector spinae muscle group (Tucker et al., 2009). Relative movement of the electrode grid and the underlying muscles and changes in muscle-shape may affect the spatial distribution of RMS amplitude. The HDsEMG grid was fixed to the skin surface by double-sided tape on the experiments in this thesis, eliminating any relocation of electrodes relative to active muscles. Moreover, the HDsEMG recordings were performed during isometric contractions to minimize the potential effect of muscle-shape. Still, small changes in sitting position was observed during the sitting, and changes of muscle shapes occur in isometric contractions (Hodges, Pengel, Herbert, & Gandevia, 2003). However, the high spatio-temporal correlation observed during sitting indicates no significant change in muscle-shape and similar location of the active MUs relative to the HDsEMG grid during the recordings.

Alternating activation

Fatigue prevention and pain intensity has shown to be inversely related to differential activation between the heads of biceps brachii and parts of the trapezius muscle (Holtermann et al., 2010; Holtermann et al., 2011). Moreover, alternating activation between synergistic muscles at the knee has shown to be related to attenuation of muscle fatigue (Motoki Kouzaki & Shinohara, 2006). Mechanical redundancy in lumbar muscles has been suggested to prevent or delay fatigue development in lumbar muscles, and variation in the activation level of parts of synergistic lumbar muscle groups could be expected to prevent excessive fatigue and muscle pain (Larivière et al., 2006; McLean, Tingley, Scott, & Rickards, 2000; van Dieën, Oude Vrielink, & Toussaint, 1993). During sustained quiet sitting in paper I and II the alternating activation between lumbar muscles on the left and right side was related to the fatigue indicators represented by MDF and RPE. This phenomenon is considered to be an

attempt to use a different mechanical or muscle strategy to perform the same task for avoiding muscle fatigue. Changes in sitting position could potentially influence alternating activation. However, only very small changes in sitting position were observed. A threshold of 30% was used to determine the periods of alternating activation, and to be recognised as true alternating activity the difference between EMG signals from left and right lumbar muscles had to exceed a threshold of 30%.

Differences between superficial and deeper muscle fibers (paper I)

Differential activation of deep and superficial lumbar muscles has been observed (G. L. Moseley et al., 2002; Tsao, Danneels, & Hodges, 2011). The EMG activity in deep lumbar muscles has been investigated by insertion of fine wire EMG electrodes into the muscle, revealing information from a small part of the muscle under investigation. Analysing the monopolar EMG signals from the HDsEMG recordings in paper I provided a non-invasive method to investigate larger part of the deep lumbar muscles. Surface EMG with monopolar leadings (1 electrode above the muscle and one not) represents EMG recordings from a larger area of muscle fibres than surface EMG from bipolar leadings (both electrodes above the muscle) that mostly represent signals from superficial motor units since the common signal present on both electrodes simultaneously is cancelled out and action potentials traveling over superficial muscle fibers are dominating (Hotta & Ito, 2011; Kleine et al., 2000; Roeleveld et al., 1997). In the trapezius muscle, monopolar and bipolar configurations showed different changes with fatigue (Kleine et al., 2000). Relatively higher muscle activation was observed in bipolar recordings in paper I. Moreover, the bipolar MDF decreased and RMS increased more than the monopolar, indicating differential activation of deep and superficial lumbar muscles.

5.4 Clinical implications

This thesis shows that cLBP patients have a normal postural strategy with increased variation of posture during sitting and standing in response to increased perception of musculoskeletal discomfort and pain. Thus, postural strategies do not contribute to the patients LBP. Despite increased variation in posture no increased variability in muscle activation was achieved. This may indicate a deficiency in relaxing muscles after activation and potentially induce a continuous low level muscle load which may contribute to the persistence of LBP.

Psychological factors have shown to be important in the transition from acute- to chronic stage of LBP (Chou & Shekelle, 2010). Plausibly the inherent uncertainty related to what the non-specific LBP represent may contribute relatively higher muscle activation level and to a deficiency in relaxing activated muscles. To address this uncertainty, patient education throughout a thorough clinical examination including a diagnostic clarification and reassurance of normal findings may give patients a new understanding of the back pain.

6.0 Summery and conclusions

The present thesis has explored the muscle activation and postural control in cLBP during sitting and standing, activities which requires low level muscle activation and is known to aggravate LBP. The overall objective of this thesis was to gain insight in muscle functioning, postural strategies and fatigue in the lumbar region during low level isometric muscle contractions related to longer periods of sitting and standing in chronic low back pain (cLBP) patients compared to healthy control subjects (HCs).

The conclusions based on the findings from this thesis are summarized as follows:

- Variation in muscle activation in lumbar muscles are related to fatigue development in lumbar muscles during sustained sitting
  - Higher frequency of alternating activation between sides of lumbar muscles is related to decrease in MDF and increase in RPE.
  - Although a subjective feeling of fatigue, no general sign of fatigue development can be detected in MDF during sustained sitting.
  - Women have no different variation in muscle activation or different fatigue development in lumbar muscles compared to men during sitting.

- Due to increased subjective feeling of fatigue, musculoskeletal discomfort and LBP the patients with cLBP have reduced tolerance for quiet sitting and prolonged standing.
  - Patients with cLBP prematurely ended the sustained sitting.
  - Significant more variable sitting position and more body weight shift during prolonged standing in cLBP patients.
  - Patients with cLBP have similar spatial and lower temporal variability in lumbar muscle activation compared to HCs.
  - Patients with cLBP do not develop more muscle fatigue during sitting and standing, but reports increased subjective feeling of fatigue and more pain compared to HCs.
- Patients with cLBP have a normal postural strategy during sitting and standing with increased postural variability in response of increased perception of musculoskeletal discomfort and pain.

  - Despite increased variability in posture in cLBP patients the muscle activation variability was similar or lower compared to HCs, in support of a reduced ability to relax muscles after activation in cLBP patients.
- Due to a normal postural strategy the patients with cLBP are not more affected by prolonged standing than HCs.
  - Similar change as HCs in strength, FRR and RE after prolonged standing.

Future research

The findings from this thesis suggest a need for future research, addressing the following issues:

- Is it possible to reveal alternating activation during low level contraction during sitting?
- Do patients with acute/ sub-acute LBP have a reduced ability to relax lumbar muscles after activation?
- What is the effect of a brief cognitive intervention program on lumbar muscle activation in LBP patients?

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Paper I

Journal of Electromyography and Kinesiology 24 (2014) 380–386

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Alternating activation is related to fatigue in lumbar muscles during sustained sitting

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ARTICLE INFO

Article history:
Received 19 March 2013
Received in revised form 27 January 2014
Accepted 31 January 2014

Keywords:
Low back
HDsEMG
Muscle fatigue
Alternating activation
Submaximal contraction

ABSTRACT

The aim of this study was to investigate the relation between variability in muscle activity and fatigue during a sustained low level contraction in the lumbar muscles. Twenty-five healthy participants (13 men 12 women) performed a 30 min sitting task with 5 degrees inclination of the trunk. Surface electromyographic (EMG) signals were recorded bilaterally from the lumbar muscles with 2 high density surface EMG grids of 9 × 14 electrodes. Median frequency (MDF) decrease, amplitude (RMS) increase and the rating of perceived exertion (RPE) were used as fatigue indices. Alternating activation and spatial and temporal variability were computed and relations with the fatigue indices were explored. During sitting, the mono- and bipolar RMS slightly increased while the MDF remained unchanged indicating no systematic muscle fatigue, although the average RPE increased from 6 to 13 on a scale ranging between 6 and 20. Higher frequency of alternating activation between the left and right side was associated with increased RPE ($p = 0.03$) and decreased MDF ($p = 0.05$). A tendency in the same direction was seen between increased spatial and temporal variation within the grids and increased RPE and decreased MDF. Present findings provide evidence for a relationship between variability in muscle activity and fatigue.

1. Introduction

The complex network of muscles in the lumbar spine consists of nearly 70 muscles of variable size. Each of the lumbar muscles is capable of several possible actions and exerts various forces and actions on the spinal motion segments (Bogduk, 2005). The numerous back muscles provide a pool of possible motor units that may be recruited to suit the needs of the vertebral column, and hence play a role in load distribution, load transfer and control of movement. How they are recruited into action and to what kind of action is poorly understood.

Muscular fatigue is the inevitable consequence of sustained contractions and is generally defined as an exercise induced reduction in the ability of a muscle to generate force or power (Gandevia, 2001). Spatial (Holtermann et al., 2010; Larivière et al., 2006) and temporal (van Dieën et al., 1993; van Dieen et al., 2009) variability in muscle activation are related to the rate of fatigue development. Moreover, females have been observed to be more fatigue resistant compared to men, and possible mechanisms for this gender difference include factors related to muscle mass, substrate utilization, muscle morphology, and neuromuscular activation patterns (Hicks et al., 2001; Larivière et al., 2006).

Muscle effort of trunk extensors during standing and sitting postures usually remains below 10% of maximum activation (Mork and Westgaard, 2005; van Dieën et al., 2001). Such low-level muscle activity can be sustained for a long time and is often accompanied by a subjective experience of fatigue (Sjogaard et al., 2004) as well as electromyographic manifestations of fatigue, like increased amplitude of the electromyogram (EMG) and a shift in the EMG power spectrum to lower frequencies (Blangsted et al., 2005; Jorgensen et al., 1988). In addition, fatigue prevention and pain intensity are shown to be inversely related to the frequency of differential activation between the heads of the biceps brachii muscle and parts of the trapezius muscle, respectively (Holtermann et al., 2010, 2011). Such a use of mechanical redundancy has been suggested to prevent or delay fatigue development also in lumbar muscles by alternating activity between muscle parts or synergistic muscles (Larivière et al., 2006; McLean et al., 2000; van Dieën et al., 1993), but has so far not been investigated in detail during low force contractions. Moreover, lumbar activation and fatigue during sustained low force contractions have rarely been studied, despite that muscle activation and fatigue have been linked to low back pain for decades (Bonato et al., 2003; De Luca, 1993; Roy et al., 1989). To our knowledge there are only two

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http://dx.doi.org/10.1016/j.jelekin.2014.01.011
1050-6411/

studies addressing this (Farina et al., 2003; van Dieen et al., 2009). Van Dieën et al. revealed electromyographic manifestations of fatigue during a very constrained lying task, while Farina et al. could not observe any fatigue related changes in the EMG signal from lumbar muscles during a less constrained standing task. In van Dieën at al's study, the development of fatigue was linked to the temporal variability in muscle activity, defined by the coefficient of variation (CV). However, the amount of variability in muscle activity during a less constrained task, e.g. sitting, and its relation to muscle fatigue remains unclear (van Dieen et al., 2009).

Furthermore, possible differences in fatigue development in deep and superficial lumbar muscle during low level muscle effort may be present due to differences in biomechanical load (Bogduk, 2005). Surface EMG with monopolar leadings (1 electrode above the muscle and the other not) represent activity from a larger area of muscle fibers than surface EMG from bipolar leadings (both electrodes above the muscle) that mostly represent signals from superficial motor units since the common signal present on both electrodes simultaneously is cancelled out and action potentials traveling over superficial muscle fibers are dominating (Hotta and Ito, 2011; Kleine et al., 2000; Roeleveld et al., 1997). In the trapezius muscle, monopolar and bipolar configurations showed different changes with fatigue (Kleine et al., 2000), while this has not been used to investigate low back muscles yet.

The aim of the present study was to investigate if electromyographic manifestations of fatigue occur in deep and superficial lumbar muscles during sustained sitting, whether such fatigue is associated with lumbar muscle variability between- (i.e. the alternating activation) or within sides (i.e. reduced temporal or spatial variation of the signal) and whether there are gender differences. We hypothesized a beneficial effect of spatio-temporal variability; increased temporal and spatial variability and low frequency alternating activation was expected to be associated with reduced fatigue development indicated by less decreased EMG frequency content, less increased EMG amplitude and less increased perceived effort. Moreover, we expected that deep and superficial lumbar muscles would have different fatigue development due to differences in biomechanical loading, and that this would result in differences between bipolar and monopolar EMG. In addition we hypothesized that female subjects, as a consequence of an expected lower trunk mass, would show less pronounced electromyographic manifestations of fatigue and report less perceived exertion.

2. Methods

2.1. Design

A cross-sectional laboratory experiment was carried out. Participants performed a 30 min sitting task with maximal voluntary back extension prior to and after this task while low back muscle activation was evaluated with high density surface electromyography (HDsEMG) and position with two inclinometers.

2.2. Participants

32 healthy adults (16 males and 16 females) without back pain in the age range 29–53 years were included in the study. The two genders were matched on age. The exclusion criteria were back pain in the previous year or back pain lasting longer than one week in the previous 3 years, surgery on the musculoskeletal system of the trunk, known congenital malformation of the spine or scoliosis, body mass index >27 kg/m^2, systemic-neurological-degenerative disease, history of stroke, pregnancy and abnormal blood pressure. After inspection of the EMG signal, 7 subjects with subcutaneous soft tissue and fascia >15 mm were excluded due to poor signal quality. Therefore, 25 subjects were included in final analyses (13 males and 12 females) of which the characteristics are summarized in Table 1. The project was approved by the Regional Committee for Medical Research Ethics (REK) in the South-Eastern Norwegian Regional Health Authority and all subjects signed an informed consent prior to participation.

2.3. Experimental setup and procedure

A custom-made questionnaire was utilized to collect the participants' characteristics. Ultrasound measurements were taken of the distance between the skin and the paraspinal muscles (subcutaneous soft tissue and fascia) 3 cm lateral of the spinous process at the L3–L4 level.

Two inclinometers were placed on the back to control the sitting position; one located on the proc spinous in the lower part of the thoracic spine (Th 12), and one on the sacrum at the S1-level. Target position (horizontal line with marked area of ±1 degree on a total figure display of 10 degrees) and real time feedback (rising bar) of the inclinometer at Th 12 was provided on an 19″ computer screen placed at a distance of ~90 cm at eye level. Data from the inclinometers was collected with a sample rate of 1500 Hz and saved in a separate file during acquisition in MyoResearch XP Master Edition (Noraxon).

Two HDsEMG grids consisting of 126 (9×14) Ag–AgCl electrodes with 4 mm inter electrode distance (IED) were attached to the skin. The skin was prepared with an abrasive paste before double-sided tape was attached to the skin. Electrode gel was applied before the electrode grids were attached to the tape. The orientation of the grid was with 9 mediolateral columns and 14 caudal–cranial rows (Fig. 1). The surface EMG data was recorded using two 128-channel ActiveTwo amplifier systems (BioSemi, Amsterdam, The Netherlands) in a "daisy-chain" configuration, with a sample rate of 2048 Hz per channel. The acquisition software (MyoDaq) was developed at the Department of Clinical Neurophysiology of the Radboud University Nijmegen Medical Center.

To determine maximum voluntary contraction (MVC) the subjects performed 3 maximal contractions of back extension against resistance of a strap around the upper part of the trunk while sitting, each lasting 5 s with 3 min rest between the contractions. After another break of 10 min, the participants were asked to maintain the target inclination of the trunk for 30 min or until "task failure", defined as a deviation from the target inclination of ±1 degree for more than 3 s. Every five minutes, subjects rated their perceived exertion (RPE) experienced during the sustained sitting on a scale ranging from 6 to 20 (Borg, 1982).

2.4. Data analyses

Prior to further analysis, HDsEMG channels with poor quality were removed. Thereafter, the signals were band pass filtered at 30–300 Hz and bipolar spatial filtered in the cranial–caudal direction (12 mm IED) leaving 99 bipolar EMG signals in 9 columns

Table 1
Subjects characteristics. Mean and standard deviation (SD) of the subjects characteristics for the 13 male (Men) and 12 female (Women) participants. Results of independent *T*-test (t) or Mann–Whitney U (U) test evaluating gender differences with the level of significance (p) are also included.

	Men Mean (SD)	Women Mean (SD)	t or U	*P*
Age (year)	39.5 (6.6)	40.2 (6.8)	0.25^t	0.81
Height (cm)	182.1 (4.7)	165.5 (4.5)	−9.03^t	<0.01*
Weight (kg)	79.5 (8.6)	59.8 (4.5)	155.5^u	<0.01*
BMI (kg/m^2)	24.0 (2.5)	21.8 (1.0)	−2.83^t	0.01*
Muscle depth (mm)	9.1 (2.3)	10.1 (2.6)	1.04^t	0.31

* Statistically significant effect ($p < 0.05$).

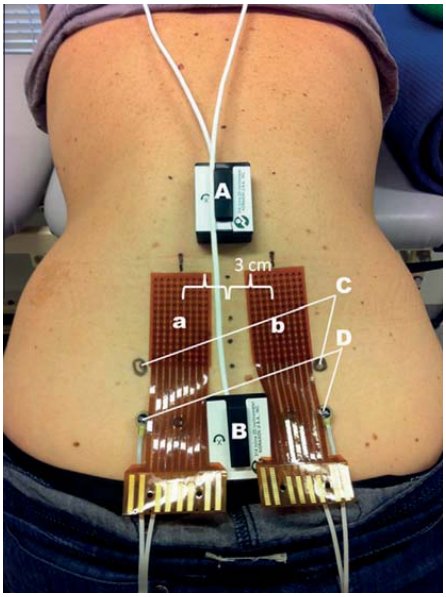

Fig. 1. The picture illustrates the placement of the electrode grid (a) and (b), 3 cm from the spine process to center of the grid and with the base of the grid in level of the posterior superior iliac spine C). (A) illustrates the placement of the trunk inclinometer, in the lower part of the thoracic spine, and (B) illustrates the placement of the pelvis inclinometer on the sacrum.

and 11 rows. For each monopolar and bipolar signal, the muscle activity level was described using the root mean square (RMS) calculated in 1 s non-overlapping time-windows and normalized to the 1 s highest RMS value (RMSmax) during the three MVCs performed prior to the sustained sitting task. In addition, median frequency (MDF) of the power density spectrum was computed in epochs of 1 s with a frequency resolution of 1 Hz.

For each grid and all epochs, the overall average RMS EMG amplitude (grid average) was obtained.

Changes in grid average RMS and MDF during the sustained contraction were quantified as the slope of a linear regression (RMSslope and MDFslope).

The variability in lumbar muscle activity between left and right side was quantified by calculation of the alternating activation between left and right lumbar muscles. Similar to the investigation of differential activation in the biceps brachii and trapezius muscles (Holtermann et al., 2008, 2011), the alternating activation was determined using the following procedure: the temporal trend throughout the contraction was removed from both grid averaged RMS signals. The detrended RMS was normalized to the second highest value of each RMS signal. The second highest value was used due to the possible effects of transient artifacts in the signals on the peak RMS value. This resulted in two signals ranging from approximately 0–1. The difference between these two signals was calculated. Alternating activation was defined as the difference between left and right RMS signals exceeding a threshold of 0.3. This implies that these differential activity instances result of an RMS increase on one side while the RMS on the other side remained unchanged or decreased, or the activity increased or decreased on both sides with different rates. However, it is unlikely that the latter caused the detected alternating activity due to threshold setting. Finally, the frequency of these periods with alternating activation (the number of activations per min) was counted.

To investigate temporal variations in amplitude, the grid averaged signals were de-trended and the temporal coefficient of variation (COV) for each grid was calculated (COV = 100 * SD de-trended RMS /mean RMS). In order to quantify RMS distribution changes, correlation coefficients were calculated between RMS values of all electrodes at one epoch with the RMS values the same electrode or electrode pair at another epoch. Correlation coefficients (CCT) were obtained for all possible combinations for recording from the sustained sitting task (1800 s) resulting in a matrix of 1800 × 1800 correlations. Median (CCT_{MED}) and coefficient of variation of all correlations (CCT_{COV} = 100 * SD CCT/mean CCT) were computed to quantify the amount and variability of the RMS distribution change during the sustained contraction. Low CCT_{MED} and high CCT_{COV} indicate a large variation in RMS distribution during the sitting.

To reduce data, all EMG parameters were averaged bilaterally.

Using the inclinometer data, for each second, the mean medio/lateral and anterior/posterior position was computed. The absolute change in position was calculated as the average position during the last minute of contraction (sitting) minus the average position during the first minute.

2.5. Statistical analyses

The statistical analyses were performed with the software PASW Statistics 19. A Shapiro–Wilk *W*-test for normality was performed on all dependent variables before statistical analysis. Parametric statistics were applied on normal distributed variables, while non-parametric alternatives were used for non-normal distributed variables. Paired statistics were applied to analyze the changes in a/p position for the pelvis. The slopes for MDF and RMS were tested against zero. Differences between men and women were evaluated by independent samples tests. Correlations were obtained between measures of variability (CCT_{MED}, CCT_{COV} and COV) and slopes of RMS, MDF and RPE. The significance level was set to $P < 0.05$, a trend to $P < 0.1$. Comparisons were performed two tailed.

3. Results

Twenty-four out of 25 participants managed to perform the 30 min sitting task. One participant was not able to maintain the sitting position for more than 20 min due to experienced perceived exertion, pain and discomfort in the sitting position. The females had a significantly lower BMI than the males, but the depth of the muscle (skin plus subcutaneous fat layer) measured by ultrasound was similar (Table 1).

Feedback was given from the trunk during the sitting, resulting in very small changes in the trunk position (mean ± SD in a/p direction 0.0 ± 0.2 degrees; m/l direction 0.3 ± 1.5 degrees). The change in pelvis position was slightly larger (mean ± SD in a/p direction 1.2 ± 2.9 degrees; m/l direction 0.1 ± 0.9 degrees). There were no significant gender differences.

RPE increased with (median (range)) 6 (9) from 6 (5) prior to 13 (11) after the 30 min sitting task, without any gender difference.

The activation level of the lumbar muscles at the start of the 30 min sitting task was on average (SD) 11(6) and 18 (8) % RMSmax obtained with mono- and bipolar leadings, respectively (Table 2). A repeated measures ANOVA with electrode leading (monopolar and bipolar) as within and gender as between subjects factors showed significant differences between monopolar and bipolar RMS ($F = 71$, $p < 0.01$) and MDF ($F = 20$, $p < 0.01$), where bipolar EMG had higher RMS (%RMSmax) and MDF (Hz) values than monopolar EMG, without gender effect ($F = 0.7$, $p = 0.41$ for RMS, $F = 0.9$, $p = 0.36$ for MDF) or interaction between gender and

electrode leading ($F = 0.4$, $p = 0.54$ for RMS, $F = 0.03$, $p = 0.88$ for MDF).

3.1. Electromyographic manifestation of fatigue

The mono- and bipolar RMS increased on average (SD) 3.3 (3.1) and 4.5 (4.4) %RMSmax during the 30 min sitting, respectively, while the monopolar and bipolar MDF remained unchanged (Table 3). A repeated measures ANOVA with electrode leading (monopolar and bipolar) as within and gender as between subjects factors showed a general increase of RMS (positive RMS slope, $F = 37$, $p < 0.01$), but no general change in MDF over time (MDF slope not different from 0, $F = 2.5$, $p = 0.12$). In addition, monopolar and bipolar RMS slopes were almost significantly different ($F = 4$, $p = 0.05$) and the MDF slopes ($F = 7$, $p = 0.01$) were significantly different, where the bipolar EMG showed larger RMS increase and MDF decrease than monopolar EMG. Moreover there was a gender effect on RMS slope ($F = 5$, $p = 0.03$) where men increased more in RMS than women, but not on MDF slope ($F = 0.1$, $p = 0.69$). Furthermore there was no interaction between gender and electrode leading in MDF slope ($F = 2$, $p = 0.22$) or in RMS slope ($F = 0.1$, $p = 0.75$).

3.2. Alternating activation and EMG variability (between and within side EMG variability)

Table 4 summarizes the EMG variability between- and within lumbar muscle sides. Alternating activation was observed in all subjects during the sustained sitting. On average the frequency of alternating activation in mono- and bipolar EMG was 8.5 min^{-1}(iqr 5.1–9.8) and 8.0 min^{-1}(iqr 4.8–9.1) respectively. The Wilcoxon sign rank test revealed no significant difference between mono- and bipolar alternating activation ($p = .23$). Mann–Whitney U test revealed no gender effect on alternating activation ($p = .11$).

The average mono- and bipolar CCT_{MED} were high (on average (range) $r = 0.93$ (0.26) and $r = 0.93$ (0.10), mono- and bipolar CCT_{MED} respectively). A Wilcoxon signed rank test shows that the temporal variation in COV was slightly, but significantly higher than the spatial variation in RMS distribution CCT_{COV} ($p = 0.01$ and $p < 0.01$ for monopolar and bipolar data, respectively). Mann Whitney U test revealed no gender effect in COV (monopolar $p = 0.73$ and bipolar $p = 0.57$), CCT_{MED} (monopolar $p = 0.94$ and bipolar $p = 0.65$) or CCT_{COV} (monopolar $p = 0.23$ and bipolar $p = 0.27$).

3.3. Associations between the alternating activation, variability of the signal and fatigue development

The correlation coefficients between alternating activation, variability in the EMG signal and fatigue development variables (ΔRPE, RMS slope and MDF slope) are shown in Table 5. The alternating activation was related to fatigue development. In bipolar signals higher frequency of the alternating activation was significantly correlated with increase in RPE (spearman's rho 0.43; $p = 0.03$). The relation between the alternating activation and decrease in MDF just missed to reach significance (spearman's rho 0.39; $p = 0.05$). In monopolar signals the sign of the coefficients show similar associations, however not statistically significant.

The associations between RPE and monopolar EMG variability measures were moderately strong (rho range 0.35; 0.41), statistically significant for CCT_{COV} ($p = 0.04$), and a trend for CCT_{MED} ($p = 0.05$) and COV ($p = 0.09$). All other associations were weak to moderate (rho range 0.17; 0.42) and did not reach statistical significance.

Furthermore, the subjective fatigue indicator (RPE) and the EMG fatigue variable (MDF slope) were negatively related (a large increase in RPE was related to a large decrease in MDF). This relation was statistically significant for the bipolar (spearman's rho −0.47; $p = 0.02$), but only a trend for the monopolar signals (spearman's rho −0.38; $p = 0.06$). There was no significant relation between MDF and RMS slopes.

Table 2
Initial activation level. Mean and standard deviation (SD) of the grid-average RMS (relative to the RMS during maximal voluntary back extension; RMSmax) and MDF of EMG collected from the lumbar muscles at the start of the 30 min sitting task obtained with mono- and bipolar leadings. Results are presented for the 13 men and 12 women separately. *F*-values and significant levels (*p*) of the gender effect resulting from the one way ANOVA are also included.

	Men Mean (SD)	Women Mean (SD)	Gender effect *F* (*p*)
Monopolar RMS (%RMSmax)	9.8 (7.3)	12.5 (3.5)	1.4 (0.2)
Bipolar RMS (%RMSmax)	17.0 (10.4)	18.77 (4.5)	0.3 (0.6)
Monopolar MDF (Hz)	97.7 (13.4)	93.4 (16.1)	0.7 (0.4)
Bipolar MDF (Hz)	109.6 (17.5)	104.5 (12.5)	0.7 (0.4)

4. Discussion

The purpose of the present study was to investigate if electromyographic manifestations of fatigue occurred in deep and superficial lumbar muscles during sustained sitting, whether this was associated with the variability of the signal and whether there were any gender differences. Below our results are discussed in light of these aims.

4.1. Manifestations of fatigue

The unchanged MDF throughout the sustained contraction indicates no general sign of local muscle fatigue, although we observed a small but significant increase in RMS and high ratings of perceived exertion, which may be interpreted as a subjective feeling of fatigue (Hotta and Ito, 2011).

The unchanged MDF and increased RMS in our study are in line with previous studies involving sustained low level contractions in lumbar muscles (Farina et al., 2003). This may partly be explained by recruitment of additional MUs to compensate the force loss in fatigued muscles (Moritani et al., 1986). The recruitment follows the "size principle" (Henneman et al., 1965), where bigger and faster motor units are recruited which may cause an increase in MDF (Gazzoni et al., 2001). The increased RMS amplitude may also be due to a Synchronization in motor unit firing, but this should also lead to a decrease in MDF (Kleine et al., 2001; Merletti and Parker, 2004), which was not observed in our data.

4.2. The relationship between variability in muscle activity and fatigue development

In support of our hypothesis, the alternating activation between sides of the lumbar muscles was related to fatigue development during sustained sitting. Higher frequency of the alternating activation was related to a decrease in MDF and increased RPE. Our results are in line with observations in earlier studies where low frequency differential activation between biceps brachii muscle compartments is related to decreased fatigue development (Holtermann et al., 2010). The exact mechanism behind alternating activity is not clear, although fatigue related feedback information via afferents to α-motoneurones, probably via interneurones has been proposed to be a mechanism in alternating activity in knee extensors (Kouzaki and Shinohara, 2006).

Table 3
EMG changes during the sustained contraction. Mean and standard deviation (SD) of the RMS and MDF slopes during the 30 min sitting task of the 13 men and 12 women. *F*-values and significant levels (p) of the intercept and gender effect resulting from the general linear model are also included.

	Men Mean (SD)	Women Mean (SD)	Intercept F (p)	Gender effect F (p)
Monopolar RMS slope (%/min)	0.16 (0.10)	0.06 (0.08)	35 (<0.01)*	7.7 (0.01)*
Bipolar RMS slope (%/min)	0.19 (0.13)	0.10 (0.13)	30 (<0.01)*	3.0 (0.1)
Monopolar MDF slope (Hz/min)	0.14 (0.30)	0.12 (0.52)	2.5 (0.13)	0.02 (0.89)
Bipolar MDF slope (Hz/min)	−0.11 (0.40)	0.03 (0.25)	0.4 (0.56)	1.0 (0.32)

* Statistically significant effect ($p < 0.05$).

Table 4
Alternating activation and spatial and temporal variation in RMS during sustained contraction. Median and range for the alternating activation, RMS distributions change (CCT_{MED}), coefficient of variation of the RMS distribution change (CCT_{COV}) and the coefficient of variation of the grid-average RMS amplitude (COV) for men and women.

	Men Median (range)	Women Median (range)	Gender effect U(p)
Monopolar alternating frequency (min^{-1})	9.4 (8.0)	7.2 (10.6)	108 (0.11)
Bipolar alternating frequency (min^{-1})	8.4 (9.2)	7.0 (8.7)	111 (0.08)
Monopolar CCT_{MED} (r)	0.92 (0.26)	0.95 (0.25)	76 (0.94)
Bipolar CCT_{MED} (r)	0.92 (0.10)	0.95 (0.08)	69 (0.65)
Monopolar CCT_{COV} (%)	7.6 (39.5)	4.2 (13.2)	101 (0.23)
Bipolar CCT_{COV} (%)	4.7 (14.0)	3.1 (6.4)	99 (0.27)
Monopolar COV (%)	10.4 (14.8)	11.6 (10.9)	71 (0.73)
Bipolar COV (%)	9.4 (21.7)	8.5 (12.6)	89 (0.57)

Table 5
Relation between RMS variation and fatigue indexes. Spearman's rho correlations between alternating activation, measures of variability and changes in perceived exertion (ΔRPE), MDF slope and RMS slope during the sustained sitting. Results of EMG variables obtained from monopolar and bipolar configurations are presented separately.

	ΔRPE	MDFslope	RMSslope
Monopolar			
Alternating frequency (min^{-1})	.30	−.24	−.06
CCTMED	.40	−.19	−.22
CCTCOV	−.41*	.28	.38
COV	−.35	.33	.20
Bipolar			
Alternating frequency (min^{-1})	.43*	−.39	−.10
CCTMED	.20	−.19	−.17
CCTCOV	−.29	.23	.23
COV	−.31	.42*	.29

* Correlations with a significant level $p < 0.05$ (two tailed; more variability, less fatigue).

In accordance with previous findings there was a moderate, but mostly just statistically not significant relation between temporal variation within the muscles and MDF and RPE (van Dieën et al., 1993).

We also expected that spatial EMG variability within the same side of the lumbar muscles would be related to decreased muscle fatigue. Although the signs of the correlations between the spatial variability measures and MDF decrease indicated such an association, this relation was weak (range of spearmans rho 0.19; 0.28) and did not reach statistical significance. Also the relation between spatial variability of bipolar EMG and RPE were similarly weak, although variability of monopolar EMG and RPE was significant (see below for discussion of differences between bipolar and monopolar results). Moreover, although not statistical significant, there was an opposite relation between spatial (and temporal) variability and RMS, where more variability had a tendency to be associated with increased RMS. This suggests that the relation between variability and higher MDF was at least partly mediated by increased motor unit recruitment and not merely by decreased muscle fatigue.

4.3. Differences between superficial and deeper muscle fibres

Bipolar EMG reflects the activity of relatively more superficial motor units than monopolar EMG (Roeleveld et al., 1997). The relatively higher bipolar compared to monopolar RMS observed at start of the sitting (∼18 versus ∼11 %RMSmax respectively) indicates that the superficial muscle fibres are more active than the deeper ones in the beginning of the sitting. Furthermore, the bipolar MDF decreased and RMS increased more than the monopolar which indicates that relatively larger and faster motor units were recruited in deep muscle structures than in superficial structures in order to maintain position during the sitting. The electrode grid utilized covers multiple muscles in the lumbar area which are subjected to different biomechanical loading during sitting (Bogduk, 2005). Deeper muscles (mostly represented in monopolar EMG) are small, and their primary function is considered to be control of load transfer and segmental motion, while superficial muscles (mostly represented in bipolar EMG) are bigger and, if bilaterally activated, extend the trunk along the sagittal plane (Bogduk, 2005). Consequently there are higher biomechanical demands on superficial muscles which partly explain the higher activation level in bipolar EMG at start and the larger increase in bipolar EMG. Moreover, the significant relation between CCT_{COV} and RPE observed in monopolar EMG may reflect changes in deep muscle layers motor recruitment due to subtle adjustments in-between lumbar spinal segments during sitting.

4.4. Gender effect

In contrast to previous studies, our results show no gender effect on the change in MDF throughout the sustained contraction. The majority of studies demonstrating less fatigable back muscles in women compared to men (Kankaanpaa et al., 1998; Mannion and Dolan, 1994) used the Sorensen test were the load involves the mass of the trunk, and decreased fatigability observed in women may be explained by lower trunk mass; less blood-flow occlusion, utilization of oxidative pathways and fatigue resistant muscle fibers and less fatigability. The sitting position in our study requires a low

contraction level in the lumbar muscles (<20 %RMSmax) possibly minimizing the impact of gender differences in trunk mass on lumbar muscle fatigue. However, the bipolar RMS increased more in men during the sitting, indicating that men recruited relatively bigger and faster motor units to maintain the sitting, possibly reflecting higher trunk mass in men versus women (Table 1).

4.5. Limitation of the study

In the present study MVC force was not recorded and consequently an unbiased index of fatigue in addition to changes in MDF, RMS and RPE is missing. This is a limitation of the study. However, we do not think this would have affected our findings.

5. Conclusions

In conclusion, although the subjects clearly indicated a subjective feeling of fatigue (large change in RPE) there was no general sign of muscle fatigue in MDF, though there were large individual variations. Our main finding was that alternating activation between sides of the lumbar muscles was related to fatigue development during sustained sitting. Higher frequency of the alternating activation was related to a decrease in MDF and increased RPE. A similar tendency was seen between increased spatial and temporal variation within the grids and decreased MDF and increased RPE. Further there was no gender effect on changes in MDF, RPE, RMS or variability measures. The relationship between the alternating activation and non-specific lumbar back pain are unknown, and future studies should focus on the possible relationship between alterations in neuromuscular activation patterns in low level muscle effort in relation to the development and maintenance of low back pain.

Conflict of interest

The authors declare no conflict of interest.

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Paper II

Reduced muscle activity variability in lumbar extensor muscles during sustained sitting in individuals with chronic low back pain

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Keywords:

Low back pain; chronic; sustained sitting; perceived exertion; muscle activation variability; Alternating activation;

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Abstract

The purpose of this study was to investigate the muscle activity variability in lumbar muscle activation within and between the right and left side of lumbar muscles in cLBP patients compared to healthy controls (HCs) during a sustained quiet sitting task. Surface electromyographic (EMG) signals were collected bilaterally from the lumbar muscles with 2 high density surface EMG grids of 9 x 14 electrodes. Between sides alternating activation, changes in RMS distribution within the electrode grids, temporal- and spatial variability of the RMS was computed. To what extent the sitting influenced the participants was evaluated by the rating of perceived exertion (RPE) and the amount of LBP on a numeric pain rating scale. Compared to HCs the cLBP patients had lower temporal ($p = 0.03$) and similar spatial variability on the muscle activation during sitting, despite a more variable sitting position. This did not result in increased muscle fatigue indicated by EMG, but the cLBP patients were more affected by the sitting as they reported higher levels of RPE during- and more LBP after the sitting and as a consequence ended the sitting earlier than HCs ($p < 0.01$). Present findings lend support to the presence of less tolerance for low-level static muscle load in cLBP patients.

Introduction

Sitting is in general associated with low biomechanical load and low level muscle activity [1]. Persons with chronic low back pain (cLBP) frequently experience increased pain during sitting, and in healthy asymptomatic subjects prolonged sitting has been associated with development and aggravation of low back pain (LBP) [2, 3].

LBP is a common health complaint with lifetime prevalence up to 84% [4]. Specific pathology (e.g. infection, tumor, osteoporosis, fracture, structural deformity) as cause of LBP is rare (<15 %), leaving the majority of LBP labelled as non-specific, or common LBP [4]. Rather than structural derangement, a functional disturbance in the complex reflex system that coordinates the network of paraspinal muscles could be the background for the impairment [5-7]. A guarded behavior and fear are major predictors for an acute episode of LBP persisting, and resulting in chronic LBP (cLBP) [4].

Altered neuromuscular function in cLBP patients has been shown during different tasks [8-11] . The muscle activation in patients with LBP is highly variable and inconsistent [12], and previous studies have mainly utilized classic bipolar electromyography (EMG) where the electrodes are placed over a small portion of a muscle and hence limited information may be obtained.

It is a challenging task to extract relevant EMG information from the complex network of muscles surrounding the lumbar spine, where nearly 70 muscles of variable size are capable of several possible actions hence exert various forces and actions on the spinal motion segments [13]. In this way the numerous back muscles provide a pool of possible “motor solutions” that may be recruited to suit the needs of the vertebral column. In contrast to classic bipolar EMG, utilizing a high density surface electromyography (HDsEMG) grid reveals

information from bigger portions of lumbar muscles and information of the spatial distribution of the electric potential over a larger surface may be excavated.

Reduced muscular endurance has been shown in cLBP patients [14] and reduced temporal variability in muscle activation is associated with increased fatigability during static low force contractions [12, 15]. Sitting is associated with rather low-level muscle activation, usually not exceeding 10% of RMSmax [1]. Presumably, this sustained low-level activity is required to fine-tune position and movements in the lumbar region. Although muscle activation and fatigue have been linked to LBP for decades [16-18], there is surprisingly little information in the literature on muscle activity in postures involving low level contractions in lumbar muscles.

Increased variation in activation of lumbar muscles seems to be related to decreased muscle fatigue during sustained quiet sitting in healthy subjects [19].The relationship between variation in activation and non-specific low back pain is unknown. Therefore, the purpose of the present study was to investigate muscle activity variability in lumbar muscle activation within and between the right and left sides of this muscle group in cLBP patients compared to healthy control persons during sustained quiet sitting. We hypothesized that cLBP patients would have less variable muscle activation and would be more affected by the sustained sitting.

Methods

Subjects

Eighteen patients (13 males and 5 females) with cLBP and 32 healthy controls (HCs; 16 males and 16 females) without back pain in the previous year or back pain lasting longer than one week in the previous 3 years in the age range 29 to 53 years were included in the study

(Table 1). Information of lumbar muscle fatigue, variation and gender differences during sustained sitting from the 32 HCs has previously been published [19]. The cLBP patients were recruited from the outpatient clinic at Vestfold Hospital Trust. Exclusion criteria were anamnesis of medical or drug abuse, surgery on the musculoskeletal system of the trunk, known congenital malformation of the spine or scoliosis, systemic-neurological-degenerative disease, history of stroke, psychiatric disorder, pregnancy and abnormal blood pressure. Patients were asked not to use any medications except for Paracetamol or Ibuprofen preparations one week before examination and not to perform any back-straining exercises 48h prior to examination.

Seven HCs with subcutaneous soft tissue and fascia > 15 mm were excluded due to poor signal quality. Therefore, 25 HCs were included in final analyses (13 males and 12 females) The project was approved by the Regional Committee for Medical Research Ethics (REK) in the South-Eastern Norwegian Regional Health Authority (S-08630a, 2008/1585) and all subjects signed an informed consent prior to participation.

Experimental setup and procedure

A custom-made questionnaire was utilized to collect the participants' characteristics. Ultrasound measurements 3 cm lateral of the spinous process at the L3-L4 level were used to determine the distance between the skin and the paraspinal muscles (subcutaneous soft tissue and fascia).

Two inclinometers were placed on the back to control the sitting position; one located on the proc spinous in the lower part of the thoracic spine (Th 12), and one on the sacrum at the S1-level. Target position (horizontal line with marked area of ± 1 degree on a total figure display of 10 degrees) and real time feedback (rising bar) of the inclinometer at Th 12 was provided

on an 19" computer screen placed at a distance of ~90 cm at eye level. Data from the inclinometers was collected with a sample rate of 1500 Hz and saved in a separate file during acquisition in MyoResearch XP Master Edition (Noraxon).

Table 1. Subject characteristics

Characteristic	*HC (n=25)*	*cLBP (n=18)*	*t or U (p)*
	Mean (SD)	*Mean (SD)*	
Age (year)	*39.9 (6.6)*	*40.8 (7.8)*	*-0.45 [t] (0.66)*
Height (cm)	*174.1 (9.6)*	*177.6 (7.9)*	*-1.27 [t] (0.21)*
Weight (kg)	*70.0 (12.1)*	*73.3 (9.6)*	*179.5 [U] (0.26)*
BMI (kg/m^2)	*22.9 (2.2)*	*23.2 (2.1)*	*-0.39 [t] (0.70)*
Muscle depth (mm)	*9.6 (2.4)*	*10.2 (3.6)*	*-0.58 [t] (0.57)*
PAL (0 – 10)	*7.2 (1.9)*	*7.4 (1.5)*	*210 [U] (0.71)*
Average pain last week (0-10)		*6 (2.6)*	
ODI		*26.9 (9.6)*	
TSK (13 – 52)		*27.1 (7.4)*	

Mean and standard deviation (SD) of the low back pain patients (cLBP) and healthy control subjects (HC) characteristics.

Abbreviations: BMI; Body Mass Index, ODI; Oswestry Disability Index, PAL; Physical Activity Level, TSK; Tampa Scale of Kinesiophobia.

Group differences evaluated with [t] independent T-test or [U] Mann-Whitney U test with the level of significance (p).

Two HDsEMG grids consisting of 126 (9X14) Ag-AgCl electrodes with 4 mm inter electrode distance (IED) were attached to the skin. The skin was prepared with an abrasive paste before double-sided tape was attached to the skin. Electrode gel was applied before the electrode grids were attached to the tape. The orientation of the grid was with 9 medial-lateral columns

and 14 caudal-cranial rows. The base of the electrode grid was at the level of the posterior superior iliac spine and placed with the center of the grids 3 cm from the spine process. The surface EMG data was recorded using two 128-channel ActiveTwo amplifier systems (BioSemi, Amsterdam, The Netherlands) in a "daisy-chain" configuration, with a sample rate of 2048 Hz per channel. The acquisition software (MyoDaq) was developed at the Department of Clinical Neurophysiology of the Radboud University Nijmegen Medical Center.

To determine maximum voluntary contraction (MVC) the subjects performed 3 maximal contractions of back extension against resistance of a strap around the upper part of the trunk while sitting, each lasting 5 s with 3 minutes rest between the contractions. After another break of 10 minutes, the participants were asked to maintain the target inclination of the trunk (5° forward inclination from vertical) for 30 minutes or until "task failure", defined as a deviation from the target inclination of ± 1 degree for more than 3 s. Every five minutes, subjects rated their perceived exertion (RPE) experienced during the sustained sitting on a scale ranging from 6-20 (Borg, 1982).

Data analyses

Prior to further analysis, HDsEMG channels with poor quality were removed. Thereafter, the signals were band pass filtered at 30 – 300Hz and bipolar spatial filtered in the cranial-caudal direction (12 mm IED) leaving 99 bipolar EMG signals in 9 columns and 11 rows. For each bipolar signal, the muscle activity level was described using the root mean square (RMS) calculated in 1s non-overlapping time-windows. In addition, median frequency (MDF) of the power density spectrum was computed in epochs of 1 s with a frequency resolution of 1Hz.

For each grid and all epochs, the overall average RMS EMG amplitude (grid average) was obtained.

Changes in grid average RMS and MDF during the sustained contraction were quantified as the slope of a linear regression (RMSslope and MDFslope).

The variability in muscle activity between sides was quantified as the alternating activation between left and right lumbar muscles. This has previously been described in detail [19]. In short, the detrended grid average RMS signal was normalized to the second highest RMS value from each signal. This resulted in two signals ranging from ca 0-1. The difference between these two signals was calculated, and alternating activation was defined as the difference between left and right signal exceeded a threshold of 0.3. This implies that these differential activity instances result of an RMS increase on one side while the RMS on the other side remained unchanged or decreased, or the activity increased or decreased on both sides with different rates. However, it is unlikely that the latter caused the detected alternating activity due to threshold setting. Finally, the frequency of these periods with alternating activation (the number of activations per min) was counted.

To investigate temporal variations in amplitude, the grid averaged signals were de-trended and the temporal coefficient of variation ($COV_{TEMPORAL}$) for each grid was calculated ($COV_{TEMPORAL}$ =100*SD de-trended RMS /mean RMS). In order to quantify RMS distribution changes, correlation coefficients were calculated between RMS values of all electrode pairs at one epoch with the RMS values the same electrode pair at another epoch. Correlation coefficients (CCT) were obtained for all possible combinations for recording from the sustained sitting task resulting in a matrix of correlations. The median value (CCT_{MED}) was computed to quantify the amount and variability of the RMS distribution change during

the sustained contraction. Low CCT_{MED} indicates a large variation in RMS distribution during the sitting.

To explore the spatial variability of the EMG amplitudes within the electrode grid during the quiet sitting, the coefficient of variation of all RMS signals in the grid was calculated during quiet sitting ($COV_{SPATIAL}$ =100*SD detrended RMS /mean RMS). The standard deviation of the detrended RMS from each bipolar signal was divided on the average RMS from each individual bipolar EMG. Low $COV_{SPATIAL}$ indicates large variability in RMS within the electrode grid during the sitting.

There was no significant difference in any EMG variable between the electrode-grids, thus all EMG parameters were averaged bilaterally.

The average medio/lateral and anterior/posterior position for each second was computed from the inclinometer data. The absolute change in position was calculated as the average position during the last minute of contraction (sitting) minus the average position during the first minute. The variability of the sitting position was investigated by the standard deviation (SD) of the sitting position.

Statistical analyses

The statistical analyses were performed with the software PASW Statistics 21. A Shapiro-Wilk W-test for normality was performed on all dependent variables before statistical analysis. As almost all variables turned out to have a non-normal distribution, non-parametric statistics were applied. For within subject changes the Wilcoxon signed rank test was performed and the Mann-Whitney U test was applied for differences between groups. The slopes for MDF and RMS were tested against zero with the one sample Wilcoxon test. The significance level for all tests was set to $p < 0.05$, and comparisons were performed two tailed.

Results

The subjects characteristics were similar in cLBP patients and HCs (all p-values > 0.1) (Table 1). Eight cLBP patients (~40 %) and one HC ended the sitting task before the scheduled 30 minutes due to experienced perceived exertion, pain and discomfort in the sitting position. On average, the LBP patients had significant shorter sitting time (median (IQR) HC; 30 (0), cLBP; 20 (23), ($p \leq 0.01$).

During the sitting, only very small changes in position were observed (all changes for trunk and pelvis position < 2.1°). However, the change in medial-lateral direction of the trunk position was significant larger in cLBP patients compared to HCs ($p < 0.01$). Moreover, during the sitting the cLBP patients had increased variation in the trunk and pelvis position compared to the HCs (Table 2). This was statistically significant (p-values ≤ 0.05) in all directions except for the anterior-posterior direction of the pelvis ($p = 0.25$). Moreover the cLBP patients reported higher RPE at the start and after the sitting and had a greater change in the RPE after the sitting (all p-values ≤ 0.02) (Table 3).

Table 2. Muscle activation during sitting.

Median and interquartile range (IQR) of the low back pain patients (cLBP) and healthy control subjects (HC) of the grid-averaged root mean square amplitude (RMS) and median frequency (MDF) of EMG collected from the lumbar muscles at the start of the sitting task and the slope of the change of these variables during sustained sitting. RMS values are presented both in uV and as a percentage of the maximal RMS obtained under a maximal voluntary contraction (%RMSmvc). U-values and significant levels (p) of the group effect resulting from the Mann-Whitney U test are also included.

	HC (n=25)	*cLBP (n=18)*	
	Median (IQR)	*Median (IQR)*	*U (p)*
Start EMG RMS (uV)	*513 (376; 1010)*	*244 (173; 517)*	*98 (<0.01)*
Start EMG RMS (%RMSmvc)	*19.5 (12.5; 25.4)*	*25.5 (17.8; 43.0)*	*147 (0.06)*
Start EMG MDF (Hz)	*103.3 (89.0; 109.3)*	*121.1 (105.0;143.9)*	*350 (< 0.01)*
EMG RMS slope (uV/min)	*3.9 (0.9; 10.1)***	*3.5 (0.2; 9.2)***	*201 (0.56)*
EMG RMS slope (% RMSmvc/min)	*0.13 (0.03; 0.28)***	*0.27 (0.05; 0.51)***	*281 (0.17)*
EMG MDF slope (Hz/min)	*-0.02 (-0.19; 0.19)*	*-0.06 (-0.29; 0.07)*	*189 (0.38)*

Muscle activation and variability during sustained sitting

The absolute RMS amplitude at the start of the sitting was lower in the cLBP patients compared to HCs ($p < 0.01$), while this value normalized to the RMS obtained during MVC had a tendency to be higher in cLBP patients (p=0.06) (Table 2). Moreover, the MDF at the start of the sitting was higher in cLBP patients ($p < 0.01$). During the sitting, both the absolute and relative RMS increased significantly in both groups (both $p < 0.01$) while the MDF remained unchanged. There were no group differences in the change of absolute RMS ($p = 0.56$), relative RMS ($p = 0.17$) or MDF ($p = 0.38$) during the sitting (Table 2).

Table 3 summarizes the EMG variability of lumbar muscles. The cLBP patients had significantly lower (p = 0.03) temporal variation (COV) in grid-averaged RMS. Alternating activation was observed in cLBP patients and in HCs, without a group difference (p = 0.56). The spatial variability of the EMG amplitudes within the electrode grids during the sitting ($COV_{SPATIAL}$) and the EMG spatio-temporal correlation (CCT_{MED}) were high without group differences ($COV_{SPATIAL}$; p = 0.46, CCT_{MED}; p = 0.56).

Table 3. Variation in posture and muscle activation during sitting.

Median and interquartile range (IQR) of the low back pain patients (cLBP) and healthy control subjects (HC) of the variables showing variation in posture and muscle activation during the sustained sitting task. Variation in posture: Coefficient of variation (COV) of the position in anterior-posterior (a/p) and medial-lateral (m/l) direction for the trunk and pelvis. Variation in muscle activation investigated by root mean square amplitude (RMS) of EMG collected from the lumbar muscles obtained with bipolar leadings. Frequency of alternating activation between the left and right side of the back muscles, the coefficient of temporal variation of the grid-average RMS (COV_{GRID}), the average coefficient of spatial variation of the RMS within the electrode grid ($COV_{SPATIAL}$) and the RMS distribution change (CCT_{MED}). U-values and significant levels (p) of the group effect resulting from the Mann-Whitney U test are also included.

	HC	*cLBP*	
	Median (IQR)	*Median (IQR)*	*U (p)*
trunk a/p SD (°)	*0.16 (0.11; 0.24)*	*0.21 (0.19;0.30)*	*315 (0.03)*
trunk m/l SD (°)	*0.41 (0.30; 0.76)*	*0.73 (0.66;1.29)*	*348 (<0.01)*
pelvis a/p SD (°)	*0.74 (0.35; 1.52)*	*0.81 (0.55 ; 1.99)*	*270 (0.27)*
pelvis m/l SD (°)	*0.26(0.20; 0.51)*	*0.47 (0.27; 1.41)*	*310 (0.04)*
EMG alternating frequency (min^{-1})	*8.0 (4.8; 9.1)*	*7.6 (4.3; 11.7)*	*201 (0.56)*
EMG COV_{GRID} (%)	*8.7 (7.4; 10.9)*	*7.0 (3.0; 9.4)*	*135 (0.03)*
EMG $COV_{SPATIAL}$ (%)	*26.1 (19.1; 34.8)*	*27.9 (16.1; 44.1)*	*255 (0.46)*
EMG CCT_{MED} (r)	*0.89 (0.83; 0.93)*	*0.93 (0.71; 0.97)*	*202 (0.57)*

** significant group difference.*

Muscle activation during maximal voluntary contractions before and after sustained sitting.

Results from muscle activation during MVC before and after the sitting are shown in Table 4. The cLBP patients had lower maximal RMS during MVC before and after the sitting ($p \leq 0.05$). Both groups had reduced RMS_{MVC} after the sitting, significant for the cLBP patients ($p = 0.04$). However, the change in RMS_{MVC} was not significant different ($p = 0.30$). The cLBP patients had higher pain ratings in the beginning and at the end of the sitting (both $p < 0.01$), and the patients increase in LBP was significant ($p = 0.01$).

Table 4. Differences from before to after sustained sitting

Median and interquartile range (IQR) of pre and post sustained sitting (SS) results in low back pain patients (cLBP) and healthy controls (HC) of muscle activation during maximal voluntary contraction in sitting trunk extension (RMS_{MVC}), rating of low back pain (NPRS) and rating of perceived exertion. Results from the Wilcoxon signed rank test (within subjects change) Z (p) and Mann-Whitney U test (group differences in change) U (p) are included.

HC n=25				*cLBP n=18*			*U (p)*
	Pre SS	*Post SS*	*Z(p)*	*Pre SS*	*Post SS*	*Z (p)*	
RMS_{MVC} (uV)	*3088 (1790 – 5345)*	*2531 (1957 – 5319)*	*-0.5 (0.6)*	*1288 (633 - 2825)*	*1224 (607 – 2950)*	*-2.1 (0.04)*	*183 (0.30)*
NPRS (0-10)	*0.0 (0.0 - 0.0)*	*0.0 (0.0 - 0.0)*	*-1.3 (0.2)*	*3.5 (1.8 – 6.0)*	*6.0 (3.5 – 8.0)*	*-2.6 (0.01)*	*370 (<0.01)*
Perceived exertion	*6.0 (6.0 – 8.5)*	*13.0 (11.0 – 15.0)*	*-4.3 (<0.01)*	*9.0 (6.0 – 13.0)*	*19.0 (17.0 – 19.3)*	*-3.7 (<0.01)*	*336 (0.01)*

Discussion

The aim of the present study was to investigate lumbar muscle activation during, and as a result of, sustained quiet sitting in cLBP patients compared to healthy controls (HCs).

The cLBP patients had on average a significantly shorter sitting time than HCs. Moreover, they developed a significant increase in pain and showed a larger increase in perceived exertion compared to HCs during the sitting. Our results support therefore the presence of less tolerance for low-level static muscle load in cLBP patients induced by the quiet sitting. This is in agreement with other studies [2, 3], and our observations during prolonged standing [20].

As instructed, during this quiet sitting task, both the HCs and the cLBP patients had very little variation in their posture. Nevertheless, this postural variation during sitting was significantly larger in cLBP patients compared to the HCs. This is also in agreement with our previous observations during prolonged (not quiet) standing, where cLBP patients changed standing posture more frequent than HCs. The perception of muscle fatigue, musculoskeletal pain and discomfort in the postural control system are believed to initiate such changes in posture [21] and it is not likely that this increased variation would cause the discomfort and pain.

The initial activation level in our study was on average about 20 % RMS_{MVC}, and somewhat higher in cLBP patients. A significant increase in RMS and RPE was observed in both cLBP patients and HCs indicating an on-going fatiguing process during sitting. The target sitting position (5° trunk inclination) in our experimental setup probably led to a higher activation level in lumbar extensor muscles during the sitting than what is usually observed (< 10 %RMSmax) [1].

Compared to HCs, the cLBP patients had reduced temporal variability in lumbar muscle activation during the quiet sitting. This is in line with observations of reduced motor variability in chronic pain conditions and linked to muscle fatigue [22]. Reduced temporal variability in muscle activity has been shown to induce local muscle fatigue even under isometric muscle contractions at a very low level [15]. Although this reduced temporal variability was accompanied by increased pain and perceived exertion in the cLBP patients,

the muscle fatigue indicators in the EMG signal (increased RMS or decreased MDF) were not different between the two groups.

During sitting, both cLBP patients and HCs had little variation in the RMS distribution over time (high CCT_{MED}; around 0.9) in lumbar muscles (Table 3). Thus, the slightly increased variation in position accompanied by a significant reduction in temporal RMS variation was not accompanied by a significant increase in variation in RMS distribution over time.

This supports the theory that cLBP patients may have difficulty to deactivate lumbar muscles despite changing sitting position, and result in constant low level isometric activity resulting in local muscle fatigue and possibly leading to musculoskeletal pain. Reduced ability to relax muscles after activation and shorter rest periods during repetitive tasks have been observed in neck pain patients [23].

The alternating activation between sides of lumbar muscles was similar in cLBP patients compared to HCs. Higher frequency of alternating activation have previously been linked to increased fatigue development during sustained sitting [19]. The exact mechanism for alternating activation is not clear, although feedback from local muscle fatigue via afferents to α-motoneurones (via interneurons) may be a plausible mechanism [24]. The cLBP patients in our study had similar signs of local muscle fatigue in the EMG signal during the sitting (similar increase in RMS) which may explain the observed similar alternating activation. Moreover, cLBP patients had increased rating of RPE (central fatigue) and pain during sitting. This indicates that central aspects of fatigue and pain may not be a factors mediating alternating activation. However, the force level of the contraction can be a considerable factor for alternate activity, and the muscle activation level observed in our study may have been too high for true alternating activation to occur.

Low maximal RMS during the MVC performed before the sustained sitting was observed in cLBP patients. Muscle activation during maximal and submaximal voluntary contractions may be inhibited by nociceptive signals via afferents to α-motoneurons via interneurons on a spinal level [12]. Further, low EMG and a high RPE was observed in cLBP patients at the start of the sitting (Table 4). This may indicate alterations in the voluntary activation of lumbar muscles, and RPE has been related to central fatigue development in submaximal voluntary contractions [25]. The increased ratings of perceived exertion at start of the sitting may indicate that cLBP patients already at the start of the sitting were influenced by static muscle activation.

Conclusions

The cLBP patients in our study had reduced tolerance for sitting, similar spatial- and lower temporal variability of muscle activation compared to HCs during sitting, despite increased variability in the sitting position. However, this did not result in increased muscle fatigue, although the cLBP patients experienced higher levels of perceived exertion and more pain during sitting. Our findings indicate the existence of a reduced ability to relax muscles after activation in cLBP patients, hence increased static muscle load, local muscle fatigue and pain. Due to the restricted sitting position, the cLBP patients experienced increased LBP and high levels of RPE and consequently ended the sitting.

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Paper III

Gait & Posture 42 (2015) 584–589

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Postural strategy and trunk muscle activation during prolonged standing in chronic low back pain patients

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ARTICLE INFO

Article history:
Received 6 March 2015
Received in revised form 26 June 2015
Accepted 1 September 2015

Keywords:
Low back pain
Chronic
Prolonged standing
Muscle fatigue
Strength
Neuromuscular control

ABSTRACT

Prolonged standing has been associated with development and aggravation of low back pain (LBP). However, the underlying mechanisms are not well known. The aim of the present study was to investigate postural control and muscle activation during and as a result of prolonged standing in chronic LBP (cLBP) patients compared to healthy controls (HCs). Body weight shifts and trunk and hip muscle activity was measured during 15 min standing. Prior and after the standing trial, strength, postural sway, reposition error (RE), flexion relaxation ratio (FRR), and pain were assessed and after the prolonged standing, ratings of perceived exertion. During prolonged standing, the cLBP patients performed significantly more body weight shifts ($p < .01$) with more activated back and abdominal muscles ($p = .01$) and similar temporal variability in muscle activation compared to HCs, while the cLBP patients reported more pain and perceived exertion at the end of prolonged standing. Moreover, both groups had a similar change in strength, postural sway, RE and FRR from before to after prolonged standing, where changes in HC were towards pre-standing values of cLBP patients. Thus, despite a more variable postural strategy, the cLBP patients did not have higher muscle activation variability, but a general increased muscle activation level. This may indicate a reduced ability to individually deactivate trunk muscles. Plausibly, due to the increased variable postural strategy, the cLBP patients could compensate for the relatively high muscle activation level, resulting in normal variation in muscle activation and normal reduction in strength, RE and FRR after prolonged standing.

1. Introduction

During periods of prolonged standing we change postural position more or less frequent, usually by shifting body weight from one leg to the other. The individuals perception of muscle fatigue, musculoskeletal discomfort and pain in the postural control system are believed to initiate these changes [1]. In fact, variation in muscle activation causing and resulting from these postural changes may be directly related to a delay in muscle fatigue, discomfort and decrease in pressure over joint tissues.

Patients with chronic low back pain (cLBP) often experience increased symptoms due to sustained low-load activities such as prolonged sitting and standing [2], and the perception of discomfort associated with prolonged standing is commonly assessed in LBP disability questionnaires [3].

A complex network, of almost 70 muscles of varying size, makes up the lumbar-spine musculature. Each one is capable of several possible tasks and exerts various forces and actions on the spinal motion segments [4]. Collectively they provide a pool of possible motor actions during load distribution, load transfer and control of spinal movement. Reasonably strong evidence exists for altered neuromuscular function and stiffened movement patterns in cLBP patients during walking, trunk flexion and unstable sitting [5–7]. Such stiffened postural control can then be seen as the cause of these muscular pain problems, or at least a factor that might explain the continuation of them.

During short periods of quiet standing (typical 60 s duration), both in cLBP patients and healthy persons, postural control has frequently been investigated through the assessment of postural sway, measured by changes in the location of the center of pressure (COP) on the supporting surface by means of a force platform.

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http://dx.doi.org/10.1016/j.gaitpost.2015.09.008
0966-6362/

However, few studies have addressed postural- and motor control strategies in cLBP patients during prolonged standing, despite its known relation to LBP. The nature of sway in prolonged standing is not the same as in quiet standing, where sway is interpreted as 'noise' in the postural control system (i.e. deficiency in balance). Large sway during prolonged standing is rather due to postural changes in terms of voluntary movements performed periodically as effective responses of the postural control system to complete the task with minimal effort [8]. To the authors' knowledge only one study included cLBP patients [2], and they solely investigated postural control. Findings from this study by Lafond et al. suggest that cLBP patients have a stiffer posture with fewer postural changes during prolonged standing compared to healthy controls (HCs), in contrast to increased displacement during quiet standing [2]. Moreover, they seem to be more affected by prolonged standing, suggesting an altered postural control system [2].

The aim of the present study was to investigate muscle activation level and variability in addition to postural control during 15 min of prolonged standing in cLBP patients compared to HCs and differences between the cLBP patients and HCs in the effect of prolonged standing on neuromuscular control, proprioception, postural sway, strength, pain and perceived effort. In line with the findings of Lafond et al. [2], we hypothesized that cLBP patients would have a postural strategy with reduced movement accompanied by increased and less variable muscle activation compared to HCs. Further we hypothesized that cLBP patients would be more affected by prolonged standing.

2. Methods

2.1. Subjects

Seventeen patients (7 male, 10 female) with cLBP and 21 HCs (8 male, 13 female) with no LBP in the previous year or LBP lasting longer than one week in the previous 3 years in the age range 31–50 were included in the study (Table 1). The cLBP patients were recruited from the outpatient clinic at Vestfold Hospital Trust. All eligible patients, diagnosed with cLBP for more than 3 months, were invited to participate. Exclusion criteria were anamnesis of medical or drug abuse, surgery on the musculoskeletal system of the trunk, known congenital malformation of the spine or scoliosis, systemic-neurological-degenerative disease, history of stroke, psychiatric disorder, pregnancy and abnormal blood pressure. Patients were asked not to use any medications except for Paracetamol or Ibuprofen preparations one week before examination and not to perform any back-straining exercises 48 h prior to examination.

All subjects signed an informed consent before enrolment, approved by the Regional Committee for Medical and Health Research Ethics (2012/1158/REK).

2.2. Participant characteristics

The height, weight, body mass index (BMI) and waist-hip ratio were obtained. A questionnaire was employed to collect the participants' age, duration of pain, average pain intensity last week and localization of pain. The Oswestry Disability Index was used to assess pain-related disability specifically related to LBP [3]. The Tampa Scale of Kinesiophobia was employed to assess fear of movement and/or (re)injury [9].

2.3. Equipment

Surface electromyography (sEMG) signals were detected with pairs of disposable sEMG electrodes (Ambu Blue Sensor M-00-S/50, 20 mm IED) bilaterally from the erector spinae (ES), gluteus medius (GM), rectus abdominis (RA) and external oblique (EO) muscles. A reference electrode was placed on S1 level. The skin at the electrode sites was shaved and abraded with alcohol, subsequently the bipolar sEMG electrodes were placed aligned with the muscle fibre direction and in accordance with European guidelines for sEMG (SENIAM) [10]. Before data collection, the signal quality was checked by visual inspection of the EMG signal during muscle contractions against light manual resistance.

A force sensor (Interface, Inc. Scottsdale, Arizona), attached horizontally to a non-elastic polyester band around the subjects torso at T6-T8 level and the wall, was used to measure the force during maximal voluntary contraction (MVC) of trunk flexion and extension, while the subject was standing in a modified "Cybex 6000 back extension module".

Ground reaction forces were recorded for each foot separately using two force plates during all tasks except for MVC (AMTI, USA; model BP400600-1000).

All data were sampled with 1500 Hz. The sEMG and force sensor data were collected with TeleMyo 2400 (Noraxon Inc., USA). Prior to digitalization, all channels were filtered with an 8th-order Butterworth low-pass filter (500 Hz), and sEMG leads were filtered with a 1st-order high-pass filter at 10 Hz. sEMG channel hardware gain was 500. Analogue output from the Noraxon system was synchronised with force plate data and stored in Qualisys Track Manager (Qualisys Medical AB, Sweden, version 2.7) and exported to Matlab R2011a (The Mathworks Inc., USA) for post processing and analyses.

2.4. Procedure

Three standing tests were performed in the following order; 60 s quiet standing, 15 min prolonged standing and 60 s quiet standing. Participants wore socks during all standing tests. During quiet standing, the participants were blindfolded and stood as still as possible with one foot on each force plate with their feet approximately at pelvis width, looking straight ahead and keeping

Table 1
Characteristics of the cLBP and healthy controls (HC). BMI: body mass index.

Characteristic	HC $n = 20$		cLBP $n = 17$		t (p)
	Mean (SD)	Range	Mean (SD)	Range	
Age (years)	40.2 (5.4)	31–50	39.0 (5.4)	31–48	.65 (.52)
Height (cm)	174.6 (8.9)	162–191	177.5 (6.5)	163–188	−1.1 (.26)
Weight (kg)	77.5 (16.7)	56–120	81.7 (15.7)	57–113	−.78 (.44)
BMI (kg/m^2)	25.2 (3.7)	20–33	25.9 (4.7)	18–38	−.48 (.64)
Waist–hip ratio	0.9 (0.1)	0.7–1.0	0.9 (0.1)	0.8–1.1	−1.6 (.11)
Duration of pain (months)			139 (119)	6–360	
Average pain last week (0–10)			5 (1.7)	3–8	
Tampa (13–54)			23.8 (8.6)	13–41	
Oswestry (%)			21.1 (7.8)	10–42	

the hands alongside their body. During prolonged standing the participants were not blindfolded. They were instructed to stand naturally with one foot on each force plate, maintain an upright posture and warned not to step off the force plates. Participants listened to a story while prolonged standing. Participants rated their LBP on a numeric pain rating scale (NPRS) before the first and after the second quiet standing. The level of perceived exertion was rated on a Borg scale [11] immediately after the prolonged standing. Before this, the reposition error (RE) [12] with eyes open and closed and the flexion relaxation ratio (FRR) tests [5], and three MVCs in trunk extension and flexion were performed, with 1 min break between contractions. After the standing tests, one MVC in trunk extension and flexion and the FRR and RE tests were performed.

2.5. Data processing

Force and sEMG data were low pass filtered with an 8th-order recursive Butterworth filter of 20 Hz and 500 Hz, respectively. In order to remove artefacts resulting from electrocardiography and movement, a 40 Hz high-pass filter was used on the sEMG signals. The choice of the relatively high cut-off frequency was based on visual inspection of the signal after filtering, still leaving enough information in the signal to sufficient answer our hypothesis [13]. For each EMG signal during FRR, MVC and quiet/prolonged standing the root mean square (RMS) was calculated in windows of 100 ms, 500 ms and 1 s, respectively, and signals from the standing tests were normalized to the 1 s highest RMS value during the three MVCs performed prior to standing. In addition, median frequency (MDF) of the power density spectrum was computed in epochs of 1 s during prolonged standing. Although the contraction was non-isometric, the 1 s epochs were stable enough to obtain good MDF values.

2.6. Data analysis

2.6.1. MVC

Trunk flexion and extension strength was determined as highest force produced during the three MVC repetitions prior to and the single MVC repetition after the standing tests and normalized to body weight (N/kg).

2.6.2. Quiet standing

Only the last 50 s from the quiet standing trials were analyzed. Ground reaction forces and moments from the two force plates were combined to calculate global center of pressure (COP). The RMS distance from mean COP (COP RMS) and COP speed, in both anterior–posterior (A-P) and medial–lateral (M-L) directions separately, and area of COP displacement (COP area) were obtained. These measures have previously been reported in studies of quiet and prolonged standing [2,8]. COP speed was defined as overall COP displacement (length of the COP trace) divided by the total time period. COP area was calculated using the principal component analysis that calculates an ellipse that fits the data [14]. The COP area corresponds to the area of the ellipse, where the data samples lie inside the 95% confidence interval.

2.6.3. Prolonged standing

From the prolonged standing, the first 10 s were removed. The number of shifts in body weight (BW) was determined. A shift in BW was defined as a change from a symmetrical stance (50% BW each leg) to an asymmetric stance (>65% BW on one leg), and the other way around. A similar definition has been used previously to look at asymmetrical standing postures [15] and postural changes during prolonged standing [16].

From the sEMG signals from each muscle the following variables were calculated; start RMS (% RMS max), slope RMS (% RMSmax/min), slope MDF (Hz/min) and coefficient of variation (COV, 100 × SD detrended RMS/mean RMS).

2.6.4. Statistics

Depending on whether or not the measures were normally distributed (Shapiro-Wilk tests), parametric or nonparametric tests were run. Nonparametric statistics were also applied if the measures had non-homogeneity of variances (Levene's test). Mann-Whitney *U* Tests and Independent Samples *T*-Tests were conducted for comparison between groups. Wilcoxon Signed Rank Tests and Paired Samples *T*-Tests were used to compare outcomes within groups from pre to post prolonged standing. All tests were performed two-tailed and statistical significance was accepted at $p < .05$. Statistical processing was conducted in SPSS version 20 (SPSS Inc., Chicago, USA).

3. Results

The subjects age and anthropometric characteristics were similar for the cLBP patients and the HCs (all p-values $> .1$) (Table 1). The cLBP patients had a large variation in pain duration (6 months and 18 years), but rather similar (about mid-scale) scores on pain intensity and LBP related disability (Table 1). One healthy participant (female) was removed from analysis due to early ended prolonged standing task.

3.1. Postural changes and muscle activation during prolonged standing

Results from prolonged standing are shown in Table 2. The cLBP patients made significantly more body weight shifts and had increased postural sway values for all COP variables compared to HCs, reaching statistical significance for COP speed and a trend for COP area and A-P COP RMS. The relative muscle activation level (% RMSmax) at the start and during the prolonged standing was higher in cLBP patients for all muscles except for GM. There was no systematic change in RMS and MDF during prolonged standing in either groups (RMS- or MDF-slopes were not different from zero). The variability in muscle activity (COV) was relatively high in GM and ES (about 30) and small in RA (about 7), without significant groups differences.

3.2. Pre and post prolonged standing tests

Results from the pre and post prolonged standing tests are shown in Table 3.

There were no significant differences between cLBP patients and HCs for any of the five COP-measures during quiet standing before or after (all p-values $> .11$) prolonged standing.

The HCs significantly increased two COP-measures and had a trend towards a significant increase in the other three ones from before to after prolonged standing. The cLBP patients only increased COP speed M-L ($p = .01$), without any group differences in changes.

Compared to HCs, cLBP patients had significantly lower trunk extension- and flexion strength before ($p < .02$) and after ($p < .05$) standing. From before to after the standing both groups reduced trunk extension and flexion strength (all $p < .01$), and this strength reduction was not significantly different between cLBP patients and HCs ($p > .11$).

The cLBP patients had on average lower FRR compared HCs both before and after standing (p-values $< .01$). There was a significant

Table 2
Centre of pressure (COP) and surface electromyography (sEMG) during prolonged standing in non-specific chronic low back pain (cLBP) and healthy controls (HC). Median (Mdn) and inter quartile range (IQR) in body weight shifts, COP area, speed and root mean square (RMS) in medio-lateral (M-L) ad anterior-posterior (A-P) direction. Mdn and IQR of initial sEMG RMS amplitude (start RMS), the RMS slope and median frequency (MDF) slope and coefficient of variation (COV) from the erector spinae (ES), external oblique (EO), rectus abdominis (RA) and gluteus medius (GM). Results from the Mann-Whitney *U* test are included.

	HC $n = 20^*$		cLBP $n = 17$		$U(p)$
	Mdn	(IQR)	Mdn	(IQR)	
Body weight shifts	3.0	(0–21)	47.0	(8–89)	98 (.03)
COParea (cm^2)	2.8	(1.3–13.3)	9.1	(4.8–20.5)	232 (.06)
COPspeed (M-L) (mm/s)	12.0	(10.1–21.6)	20.5	(14.3–27.4)	240 (.03)
COPspeed (A-P) (mm/s)	13.5	(11.1–29.5)	31.1	(15.0–40.7)	253 (.01)
COP-RMS (M-L) (mm)	13.8	(10.2–21.2)	19.7	(14.3–31.7)	233 (.54)
COP-RMS (A-P) (mm)	11.5	(6.6–51.9)	32.6	(20.9–77.5)	228 (.08)
Start RMS (%max)					
ES	7.7	5.1–10.0	12.6	8.7–18.1	90 (.01)
EO	10.6	7.2–13.3	15.2	9.7–24.2	81 (.01)
RA	4.2	2.5–5.5	6.6	3.6–13.0	97 (.03)
GM	8.3	4.9–11.6	10.4	6.3–36.5	119 (.19)
Slope RMS (% RMSmax/min)					
ES	0.2	−1.9 to 5.2	1.1	−4.6 to 12.2	161 (.68)
EO	0.7	−1.3 to 2.2	−1.4	−4.1 to 5.7	160 (.85)
RA	0.2	−0.5 to 1.1	0.3	0.1–2.1	165 (.41)
GM	−0.6	−1.7 to 3.5	−1.5	−9.1 to 7.7	138 (.66)
COV (%)					
ES	25.9	16.4–34.9	33.9	24.2–46.9	114 (.09)
EO	15.2	9.6–26.4	13.3	9.2–18.7	138 (.47)
RA	5.5	4.0–8.8	8.4	4.6–13.6	142 (.41)
GM	31.0	17.5–39.7	27.4	23.4–48.5	145 (.62)
Slope MDF (Hz/min)					
ES	3.5	−2.9 to 9.9	4.8	−16.8 to 9.0	145 (.41)
EO	3.1	−4.8 to 8.3	4.5	−7.2 to 11.1	139 (.22)
RA	−2.8	−14.0 to 7.8	−0.9	−8.6 to 7.8	145 (.29)
GM	2.5	−8.0 to 28.3	12.9	−9.0 to 21.3	158 (.28)

*Data from 19 HCs in the analysis of EMG from EO and GM due to erroneous EMG data.

decrease in FRR in both groups. The relative change in FRR was similar in cLBP patients and HCs.

In the analysis of RE three participants (one HC and two cLBP patients) were excluded from further analysis due to erroneous measurements. There were no significant differences between groups or pre to post changes in any of the RE variables or tests.

The perceived exertion after standing and the change in pain perception from pre to post standing was significantly greater in the cLBP patients compared to HCs ($p < .01$).

4. Discussion

In contrast to the observations by Lafond et al. [2], cLBP patients in our study performed more body weight shifts and had increased body sway during prolonged standing compared to HCs. Thus, our results don't show postural strategy with reduced movement in cLBP patients and consequently this may have not contributed to their LBP. The reason for this discrepant result despite no apparent differences in study population or instructions given regarding the

Table 3
Pre and post prolonged standing (PS) results in non-specific chronic low back pain (cLBP) and healthy controls (HC). Median (25–75 percentile) of postural sway variables from the quiet standing task, trunk flexion and extension strength ($FORCE_{MVC}$), flexion relaxation ratio (FRR), reposition error (RE), rating of low back pain (NPRS) and rating of perceived exertion (only post prolonged standing). Results from the Wilcoxon signed rank test (within subjects change) $Z(p)$ and Mann-Whitney *U* test (group differences in change) $U(p)$ are included.

	HC $n = 20$			cLBP $n = 17$			$U(p)$
	Pre PS	Post PS	$Z(p)$	Pre PS	Post PS	$Z(p)$	
Quiet standing							
COParea (cm^2)	138.6 (87.7–197.5)	154.8 (111.8–284.8)	−1.8 (.07)	151.6 (81.9–339.6)	190.0 (118.1–379.0)	−1.0 (.31)	165.5 (.89)
COPspeed (M-L) (mm/s)	8.3 (6.6–10.1)	8.9 (7.5–10.8)	−1.9 (.06)	7.9 (6.3–11.0)	8.5 (7.6–11.2)	−2.6 (.01)	188.5 (.58)
COPspeed (A-P) (mm/s)	8.3 (7.2–9.2)	8.8 (7.8–9.5)	−2.7 (.01)	8.6 (7.7–9.9)	8.7 (7.8–10.4)	−0.7 (.46)	138.5 (.34)
COP-RMS (M-L) (mm)	4.7 (3.7–6.3)	5.8 (4.3–7.9)	−2.0 (.04)	5.1 (3.8–6.6)	5.5 (4.5–7.3)	−1.5 (.12)	149.5 (.54)
COP-RMS (A-P) (mm)	2.1 (1.6–2.4)	2.2 (1.7–2.9)	−1.7 (.09)	2.5 (1.7–3.1)	2.2 (1.6–3.1)	−0.4 (.69)	131.5 (.24)
$FORCE_{MVC}$ (N/kg)							
Extension	9.4 (8.2–10.5)	8.4 (6.9–10.4)	−2.9 (<.01)	7.4 (6.4–9.2)	6.5 (5.5–8.2)	−3.6 (<.01)	117 (.11)
Flexion	8.6 (7.9–9.9)	7.6 (7.2–8.7)	−3.7 (<.01)	7.4 (6.6–8.8)	6.8 (5.4–7.9)	−3.6 (<.01)	144 (.44)
FRR							
FRR	10.3 (4.9–19.5)	4.8 (2.5–9.3)	−3.0 (<.01)	3.5 (2.5–7.0)	2.4 (1.8–3.0)	−3.6 (<.01)	154 (.64)
*RE (deg)**							
Eyes open	3.3 (2.1–7.6)	4.1 (2.8–8.1)	−0.8 (.45)	6.1 (2.4–11.5)	4.3 (3.1–7.9)	−1.4 (.17)	99 (.14)
Eyes closed	4.0 (2.6–6.6)	4.6 (1.8–7.4)	−0.2 (.84)	3.1 (1.9–9.8)	4.9 (3.2–9.5)	−1.5 (.149	178 (.23)
NPRS (0–10)	0.0 (0–0)	0.0 (0–0)	−1.0 (.32)	3.5 (2.0–4.0)	5.0 (3.0–7.0)	−2.9 (<.01)	53 (<.01)
Perceived exertion		7.0 (7.0–9.0)			13.5 (11.5–15.0)		32 (<.01)

prolonged standing, may be hazard, or may lay in the information patients receive under clinical examination in our hospital with the overall message that the spine is strong and will not easily suffer any injuries with normal use, it is beneficial to be physically active, and that less pain focus might facilitate natural and less painful movements [17].

Despite increased postural movements, no increased muscle activation variability in cLBP patients was observed. However, cLBP patients had increased trunk and abdominal muscle activation already at the start of prolonged standing, indicating a reduced ability to deactivate trunk muscles. Plausibly, due to the increased postural movements, the cLBP patients could compensate for the relatively high muscle activation level, resulting in a similar to HCs muscle activation variability.

The muscle activation variability in both the cLBP patients and the HCs was rather high. Variability in muscle activation is associated with decreased fatigue development [18,19], and reduced variability has been found to be related to pain development [20]. Possibly due to the high muscle activity variability, no signs of muscle fatigue could be observed in the EMG signal during the prolonged standing despite activation levels of around 10% RMSmax, while muscle fatigue development has been shown in healthy subjects during contraction levels as low as 2% RMSmax [19].

Despite this lack of muscle fatigue signs during prolonged standing, the trunk flexion and extension strength and the FRR were reduced and postural sway during quiet standing was somewhat increased after prolonged standing in both groups indicating fatigue and fatigue being a factor modifying the flexion relaxation phenomenon and postural sway [21], although fatigue has not been reported to have effect on FRR in healthy subjects previously [22].

Anyway, although the cLBP patients reported higher level of perceived exertion after prolonged standing than HCs, none of the above variables indicated more fatigue in cLBP patients compared to HCs, although other studies showed increased fatigability and less back extensor endurance in cLBP patients [23,24]. This might be related to the increased postural movements during prolonged standing in our study, while these other studies did not allow for increased movement variability in cLBP. These results could be seen in line with the original hypothesis of Lafond et al. of increased postural movements to delay discomfort and fatigue and reduce pain. Especially since neither group developed a meaningful change in pain as the HCs did not develop pain at all, while the increase of the NPRS in cLBP patients was 1.5, staying under the 2 point change which is regarded as "clinical meaningful change" [25].

The cLBP patients showed significantly lower strength and FRR both before and after prolonged standing, which is in agreement with previous reports of low strength [26] and FRR associated with LBP [5,27], indicating increased muscle activation in full flexion, like during prolonged standing.

We found no difference between cLBP patients and HCs in reposition error or in its change after prolonged standing. Fatigue has shown to significantly impair reposition of the trunk both in cLBP patients and healthy subjects [28]. Altered proprioception has been associated with LBP in some studies [29], but not in others [12]. Lafond et al. argued for a reduced proprioceptive function in cLBP patients to cause the reduced balance and stiff behaviour in cLBP patients [2]. Our results do not support this.

5. Conclusions

Contrary to the findings of Lafond et al. [2], the cLBP patients present a postural strategy with more postural variation compared to HCs during prolonged standing. Moreover, they were not more affected by standing compared to HCs. The cLBP patients showed an increased muscle activation level during prolonged standing and FRR indicating a reduced ability to individually deactivate trunk muscles. Possibly due to increased postural movements and similar muscle activation variability, cLBP patients did not develop more fatigue than HCs nor did they develop a clinical meaningful increase in LBP due to standing.

Acknowledgement

This work was supported in part by the Research Council of Norway, grant number 182006.

Conflict of interest

The authors declare that they have no competing interest or conflicts of interest. None of the authors have any financial or personal relationships that could inappropriately influence their work.

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