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214

Sami Tarnanen

Rehabilitation after Lumbar Spine Fusion

Development of an Exercise Program

JYVÄSKYLÄN YLIOPISTO

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UNIVERSITY OF JYVÄSKYLÄ

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ABSTRACT

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The purpose of the present study was to examine the performance capacity of trunk muscles in patients undergoing lumbar spine fusion (LSF) and to evaluate the feasibility of neutral spine control exercises for postoperative rehabilitation. The collected data were utilized to develop a postoperative exercise program.

This research report includes one prospective follow-up study, three cross-sectional studies, and an article presenting the RCT protocol. Trunk muscle strength, pain and disability of patients undergoing LSF were evaluated using a dynamometer, the pain VAS, and the Oswestry Disability Index (ODI) preoperatively and 3 months after LSF in 114 patients. The effect of neutral spine control exercises on trunk muscle activity was measured using surface electromyography (EMG) in 20 healthy subjects and in 22 LSF patients.

Preoperative trunk muscle strength level was low and imbalanced in the trunk extensor and flexor muscles. Mean improvement of the ODI was 47% and the decrease of the pain VAS was 65% after surgery and early recovery phase, but changes in trunk muscle function were small. Low trunk muscle strength level and strength imbalance persisted 3 months postoperatively.

Based on EMG measurements it appears that neutral spine control exercises elicit sufficient activity of the trunk muscles to improve muscle endurance and strength in healthy subjects and in LSF patients. The high trunk muscle activity and low intensity of pain (VAS range 3-16) during neutral spine control exercises justify their use in the training of trunk muscle strength in LSF patients.

Since trunk muscle strength in patients undergoing spinal fusion remains poor and imbalanced after surgery, a progressive muscle training program is needed. The present neutral spine control exercises are feasible for strength training purposes in postoperative rehabilitation. In this research, data and clinical knowledge were combined to create a postoperative rehabilitation intervention. The effectiveness of this intervention will later be tested in a randomized controlled trial.

Keywords: electromyography, exercise therapy, lumbar fusion, muscle strength, spine

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LIST OF ORIGINAL PUBLICATIONS

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I Tarnanen S, Neva MH, Kautiainen H, Ylinen J, Pekkanen L, Kaistila T, Vuorenmaa M, Häkkinen A. 2013. The early changes in trunk muscle strength and disability following lumbar spine fusion. Disability & Rehabilitation 35(2): 134-139.

II Tarnanen S, Ylinen J, Siekkinen K, Mälkiä E, Kautiainen H, Häkkinen A. 2008. Effect of isometric upper-extremity exercises on the activation of core stabilizing muscles. Archives of Physical Medicine and Rehabilitation 89(3): 513-521.

III Tarnanen S, Siekkinen K, Häkkinen A, Mälkiä E, Kautiainen H, Ylinen J. 2012. Core muscle activation during dynamic upper limb exercise in women. Journal of Strength and Conditioning Research 26(12): 3217-3224.

IV Tarnanen S, Neva MH, Häkkinen K, Kankaanpää M, Ylinen J, Kraemer W, Newton R, Häkkinen A. 2014. Neutral spine control exercises in rehabilitation after lumbar spine fusion. Journal of Strength and Conditioning Research; 28(7): 2018-2025.

V Tarnanen S, Neva MH, Dekker J, Häkkinen K, Vihtonen K, Pekkanen L, Häkkinen A. 2012. Randomized controlled trial of postoperative exercise rehabilitation program after lumbar spine fusion: study protocol. BMC Musculuskeletal Disorders; 13: 123.

ABBREVIATIONS

CLBP	Chronic low back pain
EMG	Electromyography
IQL	Inter-quartile range
LM	Lumbar multifidus
LSF	Lumbar spinal fusion
MRI	Magnetic resonance imaging
MVC	Maximal voluntary contraction
MVIC	Maximal voluntary isometric contraction
ODI	Oswestry Disability Index
OEA	Obliquus externus abdominis
OIA	Obliquus internus abdominis
PCSA	Physiological cross-sectional area
RA	Rectus abdominis
RCT	Randomized controlled trial
RM	Repetition maximum
TLF	Thoracolumbar fascia
TrA	Transversus abdominis
TUG	Timed up and go
VAS	Visual analogue scale

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1 INTRODUCTION

Chronic low back pain (CLBP) has become one of the most common causes of disability and activity limitation in adults and is consequently one of the most common reasons for work absence and early retirement in industrialized societies (Kent & Keating 2005, Thelin, Holmberg & Thelin 2008), and thus it incurs enormous financial costs to countries' social security institutions (Pohjolainen et al. 2007).

The natural course of low back pain is benign, since most low back pain episodes are mild and rarely very disabling, and therefore only a small proportion of patients seek care. However, there is no real evidence to support the general belief that 80-90% of low back pain patients become pain-free within a month (Airaksinen et al. 2006, Hayden et al. 2010). Low back pain symptoms fluctuate over time with frequent recurrences or exacerbations. Hestbaek et al. reported in their systematic review that, after an acute episode of low back pain two-thirds of patients continue to experience pain 12 months later and that 16 % of patients are still on sick leave 6 months later (Hestbaek, Leboeuf-Yde & Manniche 2003). According to another systematic review, 73% of patients had at least one recurrence within 12 months (Pengel et al. 2003). Due to the high prevalence and costs of low back pain, effective treatment for this condition is extremely important (Airaksinen et al. 2006, Hayden et al. 2010).

Due to the multidimensional nature of CLBP, developing effective treatment methods is challenging. According to several reviews, exercise is the crucial component of conservative treatment of CLBP (Hayden et al. 2005, Airaksinen et al. 2006). However, there is no consensus as to what kinds of exercises should be performed or what constitutes proper exercise dose. If conservative treatments fail to reduce severe low back pain and lower extremity symptoms, and if there are structural problems in the lumbar spine, spinal surgery is considered (Malmivaara et al. 1998).

Lumbar spinal fusion (LSF) is a surgical intervention for treating disorders of the spine, such as spondylolisthesis and degenerative disc disease. Reported lumbar fusion rates vary between 5.2 cases per 100 000 adults (publicly performed) in 2006 in Australia (Harris & Dao 2009) and 135.5 cases per 100 000 adults in 2008 in the United States (Rajaee et al. 2012). In the health care districts of Tampere University Hospital and Central Finland Central Hospital in Jyväskylä, the mean incidence of elective LSF was 25 and 30 cases per 100 000 during 2008-2012, respectively (Pekkanen 2013).

In specific disorders, the early outcome of fusion surgery has been reported to be good (Moller & Hedlund 2000, Weinstein et al. 2007). However, LSF is a demanding operation which causes structural damages to the trunk muscles. In addition, patients undergoing fusion operation have usually suffered low back pain for years, and hence functional and structural changes may have taken place in their trunk muscles (Danneels et al. 2000, van Dieen, Selen & Cholewicki 2003) and they may also have cardiorespiratory deterioration (Smeets et al. 2006).

The aim of the rehabilitation after fusion is to improve the functional capacity of trunk muscles and control of the neutral spine position to diminish loading of adjacent segments. More broadly, rehabilitation aims at activating patients and thus improving their health-related quality of life and long-term maintenance of the surgical results. In addition to back surgery operation technique used and the healing processes of tissues, the effect of exercises on trunk muscles function has to be known to optimize the effectiveness of postoperative rehabilitation. The present study focuses on evaluating changes in trunk muscle function after lumbar spine fusion and assessing the feasibility of neutral spine control exercises for rehabilitation purposes. On the basis of the findings, an evidence-based post-operative exercise program was developed.

2 REVIEW OF THE LITERATURE

The spino-pelvic complex or core is a multisegmental structure consisting of the thoracic cage, five lumbar vertebrae, the pelvic rim, and the hip joints and active tissues surrounding these joints. Further, the lumbar spine comprises the vertebral bodies and the three-joint complex of the intervertebral disc and the two posterior facet joints (Willson et al. 2005). Soft tissues such as muscles, tendons, ligaments, and fascias act to both generate motion and control motion (Behm et al. 2010). The functional role of the core is to maintain postural stability and an upright body position as well as provide mobility at the segmental level. Coordinated flexor and extensor muscle groups muscle activity is needed to assure core stability, withstand loading, and sustain postures and generate the desired spine and hip movements. Thus, the trunk and pelvic muscles have a major role in both the motion and stabilization of the spine. The functional roles of the trunk muscles should be known when selecting exercises for a trunk muscle training program. In addition, changes with age along with, pathology and back surgery modify the functions of the active and passive structures of the trunk muscles, and so also affect the selection of exercises.

2.1 Functional anatomy of the trunk muscles

The trunk muscles have three main functions: (i) control of intervertebral movement/stabilize the spine (ii) control of lumbopelvic orientation/maintain optimal alignment, and (iii) control of whole-body equilibrium (Sahrmann cop. 2002, Richardson, Hodges & Hides 2004). In addition, some trunk muscles also have essential roles in respiration (Hodges, Heijnen & Gandevia 2001) and continence (Sapsford, Clarke & Hodges 2013). The force production capacity of the trunk muscles depends on the muscle architecture, i.e. muscle length, fibre length, pennation angle, and physiological cross-sectional area (PCSA). The line of action and moment arm determine the effect of the force in producing movement, and stabilizing the spinal column (McGill cop. 2007).

2.1.1 Abdominal muscles

The rectus abdominis (RA) forms anterior and *obliquus externus abdominis* (OEA), *obliquus internus abdominis* (OIA), and *transverus abdominis* (TrA) form anterolateral abdominal wall (Neumann cop. 2002, Platzer cop. 2004). The anatomical location, long lever arm (McGill, Santaguida & Stevens 1993, McGill 1996, Jorgensen et al. 2001), and high activity level during trunk flexion in the sagittal plane (McGill, Juker & Kropf 1996, Ng et al. 2002) speak for the role of the RA in trunk flexion and posterior pelvic tilt, depending which body segment is more stable. The flexor function of the RA is needed in particular to get up from a supine position (Blondeel et al. 1997). However, the main function of the RA in daily life is stabilisation of the upper body in several functions especially in control of trunk extension e.g. during carrying a posterior load (Al-Khabbaz, Shimada & Hasegawa 2008), in support of the trunk in the push-up position (Freeman et al. 2006), and in leg lowering tasks in the supine position (Shields & Heiss 1997).

Due to long lever arms and a large PCSA, the OEA and OIA have the potential to produce trunk lateral flexion, rotation, and assist the RA in trunk flexion and posterior pelvic tilt (McGill, Patt & Norman 1988, McGill, Santaguida & Stevens 1993, Jorgensen et al. 2001, Brown et al. 2011b). The different functional roles of the OEA and OIA depend on activation patterns. If the activity is bilateral, then the muscles produce trunk flexion (Ng et al. 2002) and when acting unilaterally, they produce ipsilateral lateral flexion (Carman, Blanton & Biggs 1972). Unilateral activity of the OEA produces contralateral rotation and unilateral activity of the OIA ipsilateral rotation (Carman, Blanton & Biggs 1972, Andersson, Grundstrom & Thorstensson 2002, Urquhart & Hodges 2005). Thus, in trunk rotation, the contralateral OEA and OIA work synergistically together (Andersson, Grundstrom & Thorstensson 2002). The OEA and OIA are able to produce and control trunk motion in the sagittal, frontal, and horizontal planes. High RA, OEA, and OIA activity have been also been observed during heavy lifting, which indicate their isometric role in spinal stabilization (Escamilla et al. 2002).

It has been reported that the TrA is active during trunk rotational loading (Urquhart & Hodges 2005, Allison, Morris & Lay 2008). However, instead of production of mechanical torque, the functional role of TrA may be based on the generation of intra-abdominal pressure and tensioning of the thoracolumbar fascia (TLF) (Figure 1). In addition to TrA, the OIA is capable of these same functions (Neumann & Gill 2002, Barker, Briggs & Bogeski 2004, Barker et al. 2007). Increasing intra-abdominal pressure (Hodges et al. 2001, Hodges et al. 2003, Hodges et al. 2005) and tensioning the TLF have both been reported to increase lumbar intervertebral stiffness (Barker et al. 2006). Intra-abdominal pressure also produces the spinal unloading mechanism in all movement planes (Stokes, Gardner-Morse & Henry 2010).

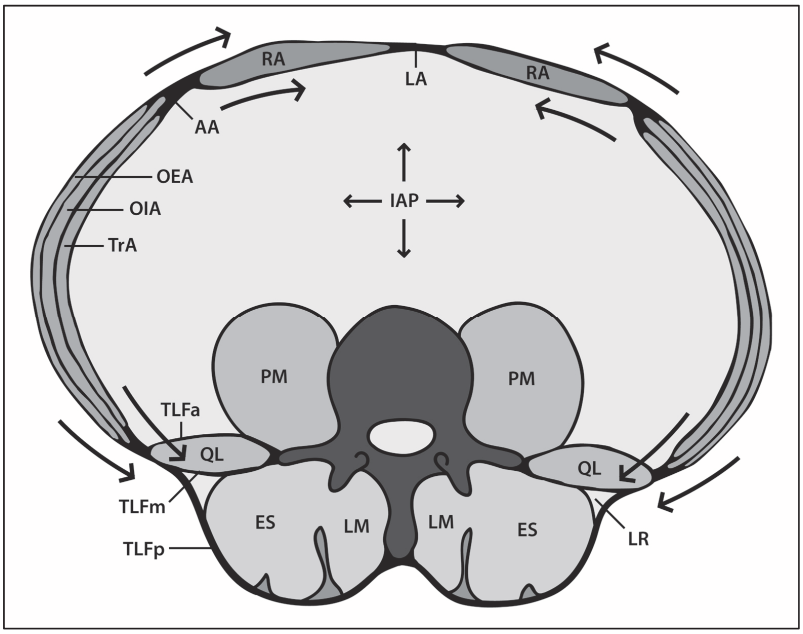


FIGURE 1 Cross-sectional view of abdominal wall and back muscles. AA=Abdominal aponeurosis, ES=Erector spinae, IAP=Intra-abdominal pressure, LR=Lateral raphe, LA=Linea alba, LM=Lumbar multifidus, PM=Psoas major, OES=Obliquus externus abdominis, OIA=Obliquus internus abdomins, RA=Rectus abdominis, QL=Quadratus lumborum, TLFa= Anterior layer of thoracolumbar fascia (TLF), TLFm=Middle layer of TLF, TLFp= Posterior layer of TLF, TrA= Transversus abdominis

The OEA, OIA, and TrA are sheet-like muscles that overlay one another, have fibres that are obliquely oriented with respect to each adjacent layer, and are tightly bound together through strong networks of connective tissue, forming the composite laminate-like structure (Brown & McGill 2009, Brown & McGill 2010, Brown 2012). Force generation and force transfer is significantly impacted by the mechanical interaction of the abdominal muscle layers (Huijing & Baan 2003, Brown et al. 2011b,). Activation of the abdominal wall muscles will influence the other muscle layers, making the intact wall a synergistically functioning muscle unit (Brown & McGill 2009). Thus, the function of abdominal muscles should be seen as one entity.

The biomechanical modeling study of Stokes et al. (2011) indicated that increased activity of abdominal muscles increased spinal stability. However, a level of muscle activity that exceeded 20 % of maximal activity did not produce any further increase in stability. Furthermore, spinal stability was not substantially influenced by the selective activation of any abdominal muscle (Stokes, Gardner-Morse & Henry 2011). Activation of a specific abdominal muscle, e.g. TrA, actually decreases control of motion and lumbar spine stability (Vera-Garcia et al. 2007). The functions of the abdominal muscles are summarized in Table 1.

TABLE 1 Functions of the abdominal muscles.

Muscle	Unilateral action	Bilateral action
Rectus abdominis	Minor role in trunk lateral flexion	Trunk flexion Posterior pelvic tilt Control of trunk extension Tensioning of the anterior aponeurosis and the linea alba
Obliquus externus abdominis	Trunk lateral flexion Contralateral trunk rotation	Trunk flexion Posterior pelvic tilt Control of trunk lateral flexion, extension, and rotation May have minor role in tensioning of the TLF
Obliquus internus abdominis	Trunk lateral flexion Ipsilateral trunk rotation	Trunk flexion Posterior pelvic tilt Control of trunk lateral flexion, extension, and rotation Tensioning of the TLF Generation of intra-abdominal pressure
Transversus abdominis	Minor role in trunk rotation	Tensioning of the TLF Generation of intra-abdominal pressure Control of the linea alba

2.1.2 Back muscles

Back muscles can be divided into three groups: (i) *psoas major*, (ii) *intertrasversarii* and *quadratus lumborum*, and (iii) lumbar back muscles (Bogduk & Twomey 1997). Further, the lumbar back muscles (behind the transverse processes of the lumbar vertebrae) can be classified into three groups: (i) short intersegmental muscles, (ii) polysegmental muscles that attach to the lumbar vertebrae, and (iii) long polysegmental muscles, which arise from the ilium and the sacrum, cross the lumbar region and attach to the thoracic cage.

The psoas major has the large cross section, muscle is able to apply high axial compression onto the spine and so increase intervertebral stiffness (Bogduk, Pearcy & Hadfield 1992, Santaguida & McGill 1995, Penning 2000), stabilize the lumbar spine in the frontal plane (Santaguida & McGill 1995, Hu et al. 2011), and control lumbar curvature in the sitting posture (Andersson et al. 1995, Park et al. 2013). It has been speculated that the quadratus lumborum, *intertransversarii,* and *interspinales* have a minor mechanical role in back function. A more probable function of the quadratus lumborum is to brace or anchor the twelfth rib and to afford a stable base for the diaphragm and thus act as a respiratory muscle (Phillips, Mercer & Bogduk 2008, Park et al. 2013). The short intersegmental muscles serve more as proprioceptive transducers that monitor the position and movements of the vertebral column and provide feedback that influences the activity of the larger multisegmental muscles of the vertebral column (Bogduk & Twomey 1997, Quint et al. 1998, Hansen et al. 2006, McGill cop. 2007).

The *lumbar multifidus* (LM) is the most medial of the lumbar back muscles (Figure 2). The deep fibres of the LM are ideally placed to increase intervertebral compression and thus control intervertebral shear and torsion (Bogduk & Twomey 1997, MacDonald, Moseley & Hodges 2006, Rosatelli, Ravichandiran & Agur 2008). The superficial part of the multifidus has a more effective movement arm for extension of the lumbar spine (Bogduk, Macintosh & Pearcy 1992). In addition, the longer fibres increase lumbar lordosis (”bowstring effect”) and the compressive and tensile loads on all vertebras and intervertebral discs interposed between its attachments (Bogduk & Twomey 1997, Rosatelli, Ravichandiran & Agur 2008). Moreover, when the lower lumbar segments are kept stationary, the LM can tilt the pelvis in the anterior direction. By tilting the pelvis in the anterior direction, the LM together with the psoas major allows a neutral lumbar spine position to be maintained during sitting (Claus et al. 2009, Park et al. 2013). The distinct functions of the deep and superficial fibres have been confirmed by EMG measurements (Moseley, Hodges & Gandevia 2002, Moseley, Hodges & Gandevia 2003). The functional role of the LM during trunk rotation is not to produce rotation, but to oppose the flexion effect of the oblique abdominal muscles as they produce rotation (Bogduk & Twomey 1997, Danneels 2007).

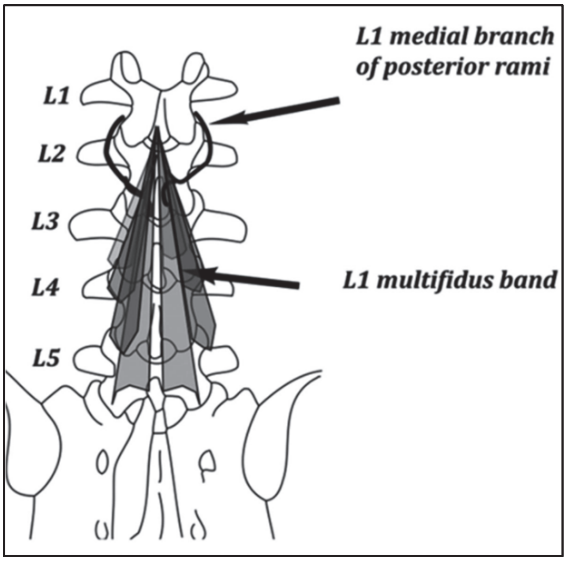


FIGURE 2 Lumbar multifidus. (Kim 2010). Reprinted with permission of Wolters Kluwer Health.

The LM has the unique morphological capacity to provide lumbopelvic stability by controlling intervertebral and sacrovertebral motion. Several factors support the role of the LM as a stabilizer of the lumbar spine.

1) The segmental arrangement and innervation of the muscle fascicles allow specific segmental control of spinal motion (Figure 2) (Kalimo et al. 1989,Bogduk & Twomey 1997, Jemmett, Macdonald & Agur 2004, Danneels 2007, Rosatelli, Ravichandiran & Agur 2008).

2) The geometry of the LM remains unchanged throughout the range of postures, which illustrates the potential of muscle to function in any physiologic posture (McGill 1991).

3) The PCSA of the multifidus is more than twice as large as that of any other muscle in the lumbar region (Ward et al. 2009a), and thus it has an essential role in producing segmental mechanical stiffness (Wilke et al. 1995).

4) The multifidus acts almost exclusively on the ascending limb of its length-tension curve as the spine flexes, which improves its capacity to provide resistance to flexion (Ward et al. 2009a).

5) The passive mechanical stiffness of multifidus is higher than in other lumbar extensor muscles (Ward et al. 2009b).

6) The activity of the LM is symmetric during asymmetric loading (Danneels et al. 2001).

The erector spinae consist of two muscles: the *longissimus thoracis* and the *iliocostalis lumborum*. Both muscles have two parts: *pars lumborum* and *pars thoracis* (Bogduk & Twomey 1997). When acting bilaterally, both muscles produce posterior sagittal rotation of their vertebra of origin. Owing to their dorsoventral orientation, they are also capable of generating posterior shear forces together with extensor moment on the superior vertebrae. Thus, they are capable to resist anterior shear forces during trunk flexion (Macintosh & Bogduk 1987, McGill cop. 2007). Unilateral contraction of these muscles can laterally flex the vertebral column (Macintosh & Bogduk 1987). The recruitment pattern of the lumbar erector spinae resembles that of the LM during different extension tasks (Claus et al. 2009, De Ridder et al. 2013).

Although the thoracic erector spinae has no attachment to the lumbar spine, it has an optimal lever arm for lumbar extension. The bilateral activity of these muscles also produces an increase in lumbar lordosis and unilareral activity causes lateral flexion of the lumbar vertebral column (Bogduk & Twomey 1997). The level of activity of the thoracal parts of the longissimus thoracis and iliocostalis lumborum have been reported to be similar, at least during high intensity extension exercises (De Ridder et al. 2013). The functions of the back muscles are summarized in Table 2.

TABLE 2 Functions of back muscles.

Muscle	Unilateral action	Bilateral action
Psoas major	Hip flexion	Hip flexion Production of intervertebral stiffness via axial compression Control of lumbar spine in frontal plane Anterior pelvic tilt

		Control of lumbar spine position in sitting posture
Quadratus lumborum	Lateral flexion	Control of lumbar spine in frontal plane Stabilization of 12th rib
Intertransversarii and interspinales	Proprioceptive role Minor capacity in torque production	Proprioceptive role Minor capacity in torque production
Lumbar multifidus		Posterior sagittal rotation of lumbar vertebrae Control of flexion of the lumbar spine Increase of lumbar lordosis Increase of intervertebral compressive load and stiffness Anterior pelvic tilt
Longissimus thoracis pars lumborum	Lateral flexion of lumbar spine	Posterior sagittal rotation of lumbar vertebrae Produce posterior translation of lumbar vertebrae Control of anterior translation of lumbar vertebrae Anterior pelvic tilt
Longissimus thoracis pars thoracis	Trunk lateral flexion	Trunk extension Increasing of lumbar lordosis Anterior pelvic tilt
Iliocostalis lumborum pars lumborum	Lateral flexion of lumbar spine	Posterior sagittal rotation of lumbar vertebrae Produce posterior translation of lumbar vertebrae Control of anterior translation of lumbar vertebrae Anterior pelvic tilt
Iliocostalis lumborum pars thoracis	Trunk lateral flexion Minor role in trunk rotation	Trunk extension Increasing of lumbar lordosis Anterior pelvic tilt

2.1.3 The connective structures between trunk muscles

Both the abdominal aponeurosis and thoracolumbar fascia (TLF) have an essential role in the trunk muscle function. The RA is contained in rectus sheath, which consists of the aponeuroses of other abdominal muscles. Aponeuroses cross the midline in the linea alba between the right and left part of the RA (Rizk 1980). Thus, the RA may have role in contributing to the tensioning of the anterior aponeurosis and the linea alba to provide a stable base from which the anterolateral abdominal muscles can create force (Brown & McGill 2008b). TrA activity during trunk rotation may also be related to control of the linea alba, while the contralateral OEA and ipsilateral OIA contribute the torque (Hodges 2008). It has also been reported that the abdominal aponeuroses, and especially the linea alba, have a very important role in contributing to the mechanical stability and stiffness of the abdominal wall (Axer, von Keyserlingk & Prescher 2001, Hernandez-Gascon et al. 2013). Enhanced aponeurosis stiffness of the abdominal wall improves its force-generating potential (Brown 2012)

The TLF is the fascia of the back (Figure 1). It is the primary link between abdominal muscles and the lumbar spine. It has the capacity to transmit tensile forces produced by abdominal muscles, serratus posterior inferior, trapezius, and also by the *latissimus dorsi* and *gluteus maximus* (Vleeming et al. 1995, Bogduk, Johnson & Spalding 1998, Barker et al. 2007, Loukas et al. 2008, Schuenke et al. 2012, Willard et al. 2012, Barker et al. 2014). The TLF also acts as a passive biomechanical component due to capacity to resist high tensile stress. The length of the TLF is increased during flexion movement and strain-energy is stored to the connective tissue in the TLF. Stored energy can be released during extension and reduce the need for activation of the trunk extensors (Adams & Dolan 2007). It has been suggested that any muscle that can resist the narrowing of the TLF during stretching by applying lateral traction force is applying an extensor force to the lumbar spine (Barker & Briggs 2007). It has been proposed that, via the TLF, trunk muscles apply extension moment, in particular, to the lower regions of the lumbar spine (Gatton et al. 2010). Due to its anatomical position, the TLF can generate extensor moment with low compression forces on the vertebral column (Adams & Dolan 2007).

The TLF may improve the contraction capacity of lumbar extensor muscles via the so-called “hydraulic amplifier” mechanism. By enclosing lumbar extensor muscles and restricting their radial expansion during contraction, the middle and posterior layer of the TLF with the paraspinal retinacular sheath may increase the efficacy of paraspinal muscle force production (Hukins, Aspden & Hickey 1990, Barker & Briggs 2007, Schuenke et al. 2012).

2.1.4 Neuromuscular control of the lumbar spine

The lumbar spine is an unstable structure. Without muscles, the osteoligamentous lumbar spine would be unable to tolerate compressive load due to the weight of the upper body (Crisco et al. 1992, McGill et al. 2003). The stability of the lumbar spine is dependent on the stiffness derived from passive structures and from spinal muscles, both of which are directly and indirectly dependent on activity controlled by the central nervous system. The central nervous system determines the requirements for stability and plans strategies to meet current demands. Stable function of the lumbar spine is possible only with continuous sensory feedback and reflex dynamics. Thus, proprioceptive information regarding the position and motion of the intervertebral joint and lumbopelvic complex is needed (Solomonow et al. 1998, Hodges & Cholewicki 2007, Solomonow 2011). The function of the system is dependent on the precision with which the trunk muscles can be controlled and on the capacity of the trunk muscles to generate force (Figure 3) (McGill et al. 2003, Reeves, Narendra & Cholewicki 2007).

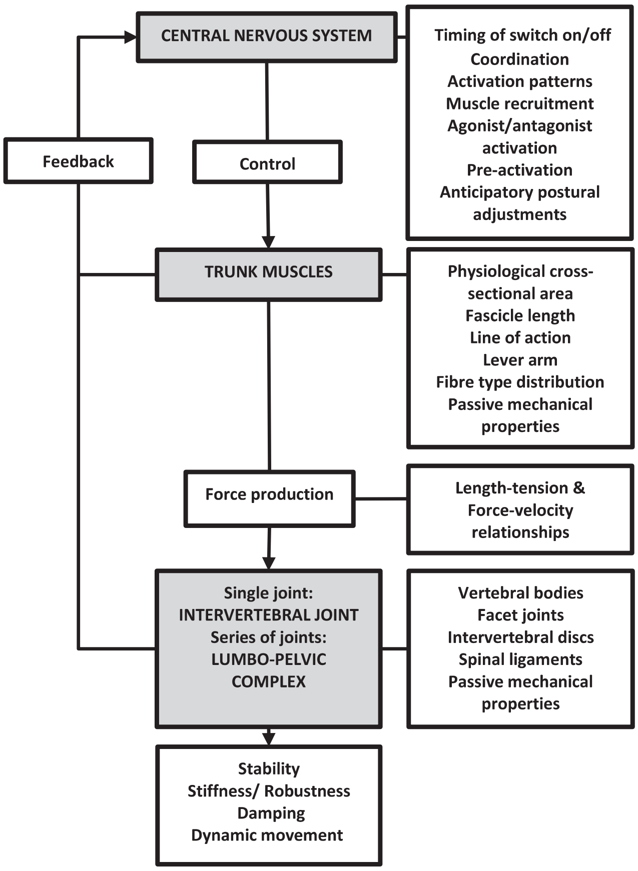


FIGURE 3 Spinal control. (Modified from (McGill et al. 2003, Panjabi 2006, Reeves, Narendra & Cholewicki 2007, Solomonow 2011).

Motor control of the trunk must meet two biomechanical needs: (i) control of regional orientation and (ii) control of individual motion segment translation and rotations while accomplishing regional orientation (Pickar 2013). A key factor in the control of spinal stability is *the prevention of buckling*. If the spine is moving and is perturbed from the intended trajectory, the central nervous system must respond to control buckling and return the spine to the intended trajectory, i.e. to maintain *the stability of the motion* (Reeves, Narendra & Cholewicki 2007, Lee, Hoozemans & van Dieen 2010, Lee, Hoozemans & van Dieen 2011).

It has been proven that coactivation of the trunk extensor and flexor muscles increases *stiffness of the lumbar spine* in the upright position. The increase in muscle and joint stiffness enhances robustness, decreases the perturbation amplitude, and decreases the time to return to initial state. Sufficient stiffness can be achieved with low levels of co-contraction of the abdominal and back muscles (Cholewicki, Panjabi & Khachatryan 1997, Granata & Wilson 2001). No one muscle can as be identified as the most important for the stiffening function. The contribution of different trunk muscles to lumbar spine stiffness or stability change constantly in accordance with many factors, including the task, magnitude of load, posture, and direction of movement (Cholewicki & VanVliet 2002). In functional activities, trunk muscle coactivation occurs before movement of the upper or lower extremities, and thereby creating a stable foundation for movement (Zazulak, Cholewicki & Reeves 2008). Spinal stiffening by coactivation of the trunk muscles provides a simple solution for the central nervous system in controlling the demands for spinal stability in a static sense (Hodges & Cholewicki 2007, Reeves, Narendra & Cholewicki 2007).

Trunk extensor-flexor coactivation strategy is normally used during high loading tasks, such as lifting, in which the load is unpredictable, and when the risk for spine injury is higher (van Dieen, Kingma & van der Bug 2003, Vera-Garcia et al. 2006). However, spinal stiffening is not an ideal control strategy in all loading situations, because increased compressive load on the spine for an extended period may lead to changes in spinal structure and increase the risk for low back pain (Granata & Wilson 2001, Shirazi-Adl et al. 2005). In addition, it is an energetically inefficient strategy and may limit the performance of dynamic tasks (Hodges & Cholewicki 2007). The response of the superficial muscles is linked to the direction of force, whereas the activity of the TrA and deep part of the LM is independent of the direction of force (Hodges 2003). During dynamic movement, controlled activation of the LM and TrA might provide a strategy to simplify the control of intervertebral translation and ensure sufficient stability of the lumbar spine without requiring a concurrent increase in activity of the larger torque producing trunk muscles and compromising the intended movement trajectory (Saunders, Rath & Hodges 2004, McCook, Vicenzino & Hodges 2009).

In addition to controlling the movement and stability of the lumbo-pelvic complex, the trunk muscles also have other functions such as those related to *respiration* and *control of postural balance.* Under certain conditions the coordination of these functions is compromised. This has been observed e.g. during intensive lifting tasks where abdominal muscle activity is needed simultaneously to maintain spinal stiffness and to assist in respiration. The reduced contribution of the trunk muscles to spinal stability during periods of increased respiratory demand, compromise control of spinal stability during lifting (McGill, Sharratt & Seguin 1995). On the other hand, increased spinal stiffness reduces the amount of movement required for other functions such as maintain postural balance (Reeves et al. 2006).

2.2 Chronic low back pain

Chronic low back pain is a complex phenomenon and its specific causes normally remain unidentified. Many hypothetical models on the development of chronic low back pain have been introduced in the literature (Taimela & Luoto 1999, Panjabi 2006, Langevin & Sherman 2007, Solomonow et al. 2012, Hodges 2013). These models can be used (i) to explain the causal connections of findings to low back pain, (ii) to develop more precise diagnostic methods, and (iii) to design more efficient treatments for back pain. However, integrative models are needed to understand the complex nature of chronic low back pain (Taimela & Luoto 1999, Hodges 2013) (Figure 4).

CLBP patients experience impairment in the passive and active tissues, neuromuscular feedback loops at different levels within the central nervous system, and also structural, functional and neurochemical changes in the brain (Ebenbichler et al. 2001, van Dieen, Selen & Cholewicki 2003, Wand et al. 2011). These changes can be observed in the control functions of the central nervous system, capacity for force production, and stability and stiffness of joint/joints. The deficiencies in spinal control, force production, and joint function are interdependent (Taimela & Luoto 1999, Hodges 2013).

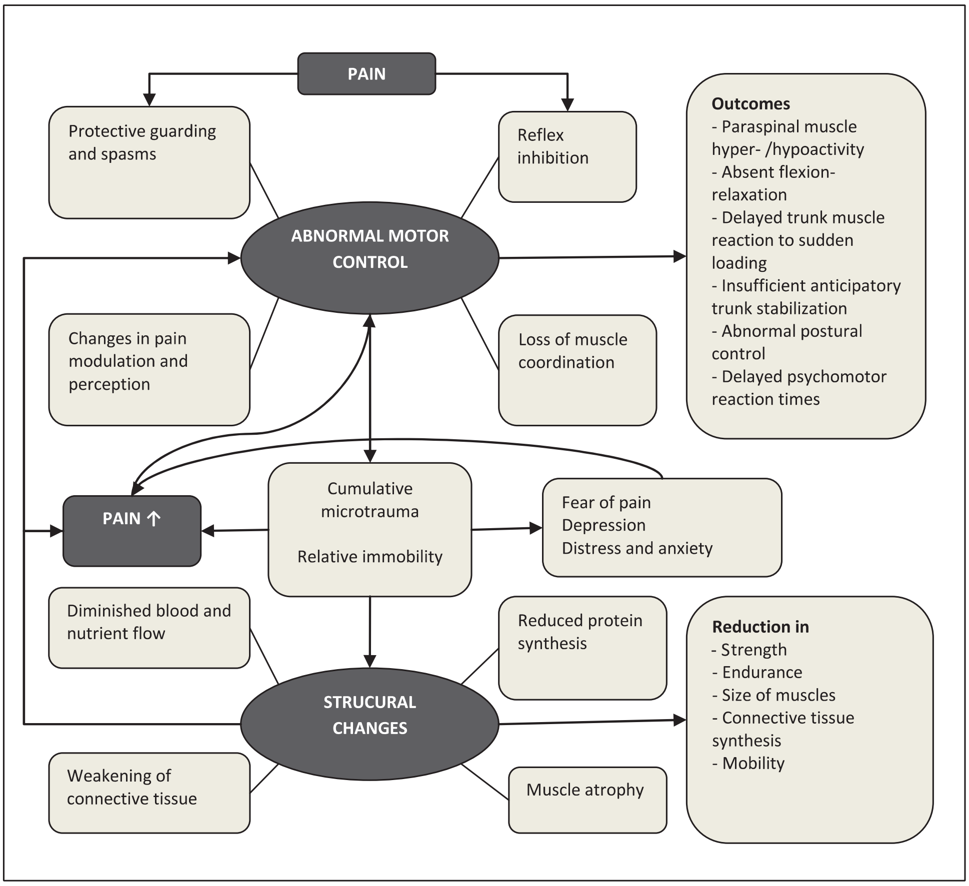


FIGURE 4 Pathophysiological model of chronic low back pain (Taimela & Luoto 1999).

The causal relationship between structural and functional changes and the development of low back pain is unclear. Only four studies have attempted to elucidate the cause-effect relationship between back injury and muscle function (Cholewicki et al. 2005, Hodges et al. 2006, Hodges et al. 2009, Brown et al. 2011a). Experimentally induced disc degeneration has been found to lead to rapid atrophy and fatty infiltration of multifidus muscle (Hodges et al. 2006) and to increased paraspinal muscle motor excitability (Hodges et al. 2009). In addition, an animal study by Brown et al. (2011a) found that disc injury also increases the stiffness of both individual multifidus muscle fibres and fibre bundles. It has been also reported that delayed abdominal muscle response to spinal perturbation increases the likelihood of low back injuries (Cholewicki et al. 2005).

2.2.1 Specific changes in trunk muscle structures and functions in chronic low back pain patients

In patients with CLBP, LM atrophy has been quantified in several studies in terms of both decreased muscle size and alteration in muscle consistency (fatty or connective tissue infiltration) (Danneels et al. 2000, Hides et al. 2008, Wallwork et al. 2009). The structural changes in LM appear to be specific and localized in nature, typically manifesting at the lowest vertebral level on the symptomatic side (Barker, Shamley & Jackson 2004, Hides et al. 2008). In CLBP patients, LM muscle atrophy has been reported to be associated with duration of symptoms (Barker, Shamley & Jackson 2004) and leg pain (Kader, Wardlaw & Smith 2000). The amount of fat infiltration in the LM is also strongly associated with low back pain (Kjaer et al. 2007). There is some evidence that in CLBP patents compared with healthy controls the paraspinal muscles have a significantly higher proportion of fast-twitch glycolytic type-IIB fibres than slow oxidative type-I fibres (Mannion et al. 1997). In addition to structural changes in the LM, decreased cross-sectional area of the psoas major and quadratus lumborum has been reported in CLBP patients (Barker, Shamley & Jackson 2004, Kamaz et al. 2007).

In comparison with healthy individuals, trunk extension and flexion strength and endurance and hip extensor endurance in low back pain patients are diminished (Mayer et al. 1985, Holmstrom, Moritz & Andersson 1992, Lee, Ooi & Nakamura 1995, Takemasa, Yamamoto & Tani 1995, Kankaanpää et al. 1998, Bayramoglu et al. 2001). It has been demonstrated that trunk extensor strength is affected more than flexor strength. The trunk extension/flexion strength ratio, which is normally 1.15-1.3 in the healthy population, is below 1.0 in CLBP patients. The changed strength ratio indicates functional imbalance between the trunk extensor and flexor muscles (Mayer et al. 1985, Takemasa, Yamamoto & Tani 1995, Yahia et al. 2011). Neuromuscular factors, such as muscle cross-sectional area (Keller et al. 1999, Lee et al. 2012), muscle density (Hultman et al. 1993), and muscle activity (Cassisi et al. 1993) explain the decrease in muscle strength in CLBP patients. In addition, the cognitive perception of pain, the anticipation of pain, the fear–avoidance belief about physical activities (Al-Obaidi et al. 2000), psychological disturbance, negative back beliefs (Mannion et al. 2011), pain catastrophizing (Lariviere et al. 2010), and pain on exertion (Keller et al. 1999) may affect strength characteristics.

Dysfunction of the neuromuscular system with respect to proprioception and motor control has been indicated by several studies. CLBP patients' postural control is decreased, they are less able to use the hip strategy to maintain balance, and they have a greater dependence on visual feedback during postural tasks (Luoto et al. 1998, Radebold et al. 2001, Mok, Brauer & Hodges 2004). Patients have significant impairments in lumbar spine and sacral position sense as evaluated by the ability to reproduce a predetermined lumbar spine and sacral tilt posture, the ability to sense a passive change in lumbar spine position, and to determine the movement direction of the spine (Gill & Callaghan 1998, Taimela, Kankaanpää & Luoto 1999, Brumagne et al. 2000, O'Sullivan et al. 2013). CLBP patients have delayed trunk muscle latencies and poorly coordinated agonist-antagonist responses to postural perturbation (Radebold et al. 2000, Radebold et al. 2001). Activation of the TrA and LM have been observed to be reduced and delayed in low back pain patients (Hodges & Richardson 1996, Ferreira, Ferreira & Hodges 2004, MacDonald, Moseley & Hodges 2009, MacDonald, Moseley & Hodges 2010).

Although people with CLBP exhibit variability in adaptation of trunk muscle function, it has been suggested that the central nervous system might adapt to pain or injury by increasing spinal stiffness. The central nervous system appears to stiffen the spine with reduced flexibility of movement choices, further decreasing the potential for error, limiting the impact of perturbation, compensating for reduced joint stability, and limiting the potential for further injury (van Dieen, Selen & Cholewicki 2003, Hodges & Cholewicki 2007). Changes in trunk stiffness and trunk muscle activity are also associated with pain-related psychological factors in low back pain patients (Thomas et al. 2008, Karayannis et al. 2013).

2.2.2 Classification of low back pain

According to the pathophysiological classification, low back pain can be divided to three groups: 1) Red flags, which accounts for about 1-2% of patients (fractures, tumors, infections, cancer); 2) Specific low back pain or radicular pain due to nerve root irritation, which accounts for about 5-10% (disc herniation, spinal stenosis, and spondylolisthesis); and 3) Non-specific low back pain, which accounts for the remaining 85-95% of patients (O'Sullivan 2005, Waddell 2005). Classification of back pain can also be based for the duration of symptoms: acute 0-6 weeks, subacute 6-12 weeks, and chronic 12 weeks or longer (Dionne et al. 2008).

In their systematic review, Fairbank et al. (2011) found 28 different clinical classification systems for CLBP. Some of these systems were descriptive, some prognostic, and some were attempts to direct patients for treatments. However, not one of these systems can be applied for all purposes. Fairbank et al. (2011) suggested developing a classification system that helps to direct the patient for both surgical and nonsurgical treatments. In another review, Karayannis et al. (2012) found five movement-based classification systems that, are widely used in physiotherapy. According to O'Sullivan's system of classification, patients can be classified into groups for surgical/medical or multidisciplinary/conservative treatment (Figure 5) (Fersum 2011). The efficacy of therapy based on O'Sullivan classification, has already been demonstrated in randomised controlled trials (Sheeran et al. 2013, Vibe Fersum et al. 2013).

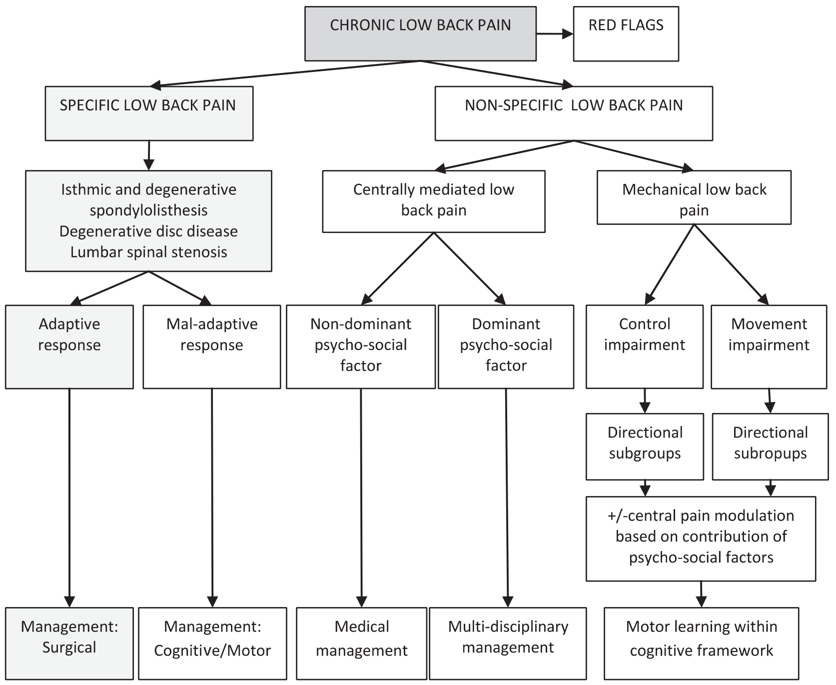


FIGURE 5 O'Sullivan classification system of chronic low back pain (Adapted from Fersum 2007). Reprinted with permission of Elsevier.

Isthmic and degenerative spondylolisthesis and lumbar spinal stenosis can be classified as specific causes of low back pain. The term spondylolysis refers to an osseous defect in the pars interarticularis of the vertebra (Hu et al. 2008). The vast majority of defects occur at L5 (85-95%) which is the vertebra subjected to the greatest amount of stress associated with daily activities (Standaert & Herring 2000, Leone et al. 2011). Incidences vary across population subgroups (gender, race, engaging in certain sporting activities). In the general population, the incidence is estimated to be about 6-8 % (Standaert & Herring 2000, Leone et al. 2011), but higher incidence rates have also been reported (Kalichman et al. 2009). The etiology of spondylolysis is probably multifactorial, with a stress fracture occurring through a congenitally weak or dysplastic pars interarticularis. It has been estimated that 15% of individuals with a pars interarticularis defect had progression to *isthmic spondylolisthesis* (Beutler et al. 2003).

Degenerative spondylolisthesis is a secondary instability caused by osteoarthrosis, in which the degeneration of the facet joints and disc result in the forward slippage of the vertebra (Hu et al. 2008). As opposed to isthmic spondylolisthesis it occurs most often at L4-L5 (85%) (Hu et al. 2008). The prevalence of degenerative spondylolisthesis increases after the 5th decade of life and is more common in females than males. Possible predisposing factors are pregnancy, general joint laxity, sagittal orientation of facet joints, and an increased pedicle-facet angle (Sengupta & Herkowitz 2005).

Lumbar spinal stenosis refers to anatomical reduction of the spinal canal, and is associated with clinical symptoms (Siebert et al. 2009, Genevay & Atlas 2010). Spinal stenosis can be classified according to etiology (primary and secondary) and anatomy (central, lateral, foraminal or any combination of these locations). Primary stenosis is caused by congenital abnormalities and secondary stenosis is caused by degenerative changes.

Lumbar spinal stenosis can be caused by various factors which are related to degenerative processes of the lumbar spine. Degenerative lumbar spinal stenosis results from a decrease in the anteroposterior and/or trasversal diameter of the spinal canal which may be caused by bulging of the intervertebral disc, osteophytes of the vertebral endplates, and hypertrophy of facet joints, joint capsule, ligamentum flavum, or posterior longitudinal ligament. Lumbar spinal stenosis may also be related to degenerative spondylolisthesis. Most frequently, lumbar spinal stenosis involves disc L4-L5 followed by L3-L4, L5-S1, and L1-L2 (Szpalski & Gunzburg 2003, Joaquim et al. 2009, Siebert et al. 2009). Signs and symptoms are thought to result from vascular compression to the vessels supplying the cauda equina or from direct pressure on the nerve root complex by the degenerative changes. Lumbar spinal stenosis induces neurogenic claudication, leg and back pain, and other leg symptoms (fatigue, weakness, paresthesia). However, radiological lumbar spinal stenosis is not necessarily the cause of symptoms, since up to 20% of asymptomatic subjects have imaging findings consistent with spinal stenosis (Genevay & Atlas 2010).

Degenerative disc disease is a complex aging-related degenerative process. In degenerative disc disease, degeneration occurs at a faster rate, rendering it a condition often encountered in individuals of working age (Taher et al. 2012). The degeneration of a painful disc may originate from the injury and subsequent repair of anulus fibrosus, which later may cause the ingrowth of vascularized granulation tissue along torn fissures, extending from the external layer of the anulus fibrosus into the nucleus pulposus (Peng et al. 2006, Adams, Stefanakis & Dolan 2010). It is probable that both overloading and immobilization can induce tissue injury and/or adaptive changes resulting in disc degeneration. Adverse mechanical conditions can be due to external forces, or may result from impaired neuromuscular control of the paraspinal and abdominal muscles (Stokes & Iatridis 2004, Adams, Stefanakis & Dolan 2010). Degenerative disc disease can result in abnormal segmental motion and biomechanical instability, causing pain. However, the relationship between instability and degenerative disc disease is not clear (Inoue & Espinoza Orias 2011).

Conservative treatment of spondylolisthesis, lumbar spinal stenosis, and degenerative disc disease may include medication, bracing, physiotherapy modalities for pain relief, manual therapy, strengthening/stabilization exercises, aerobic conditioning, behavioural treatment and multidisciplinary rehabilitation (Joaquim et al. 2009, Kalichman et al. 2009).

2.3 Lumbar spine fusion

Lumbar spine fusion (LSF) is the most intensive method of treating low back pain. LSF is considered if conservative treatment fails to decrease pain and disability and if radiographic findings on the lumbar spine are able to explain the symptoms. LSF has been advocated for a variety of conditions that affect the spine, including treatment of painful motion segments secondary to degenerative processes, and discogenic pain. The most common diagnoses for LSF are isthmic or degenerative spondylolisthesis, degenerative disc disease, and spinal stenosis (Deyo et al. 2005). The goal of the LSF is to achieve fusion between vertebrae and in that way decrease pain and disability and improve the functional capacity and quality of life of patient.

Spinal fusion can be implemented via multiple approaches: posterior, posterolateral and interbody fusion. After the emergence of pedicle screw fixation devices in the 1980s, posterolateral fusion with instrumentation has become the most common approach (Figure 6). Pedicle screw fixation with adjoining rods is thought to provide initial immobilization allowing an environment for fusion to occur, permit correction of deformity, and enable immediate post-operative mobilization of the patient. The main disadvantage of this posterior approach is the injury to the stabilizing posterior muscles of the spine and their nerve supply. This may also be a source of postoperative pain and loss of function in some LSF patients (Hanley & David 1999, Pradhan et al. 2002, Babu et al. 2011).

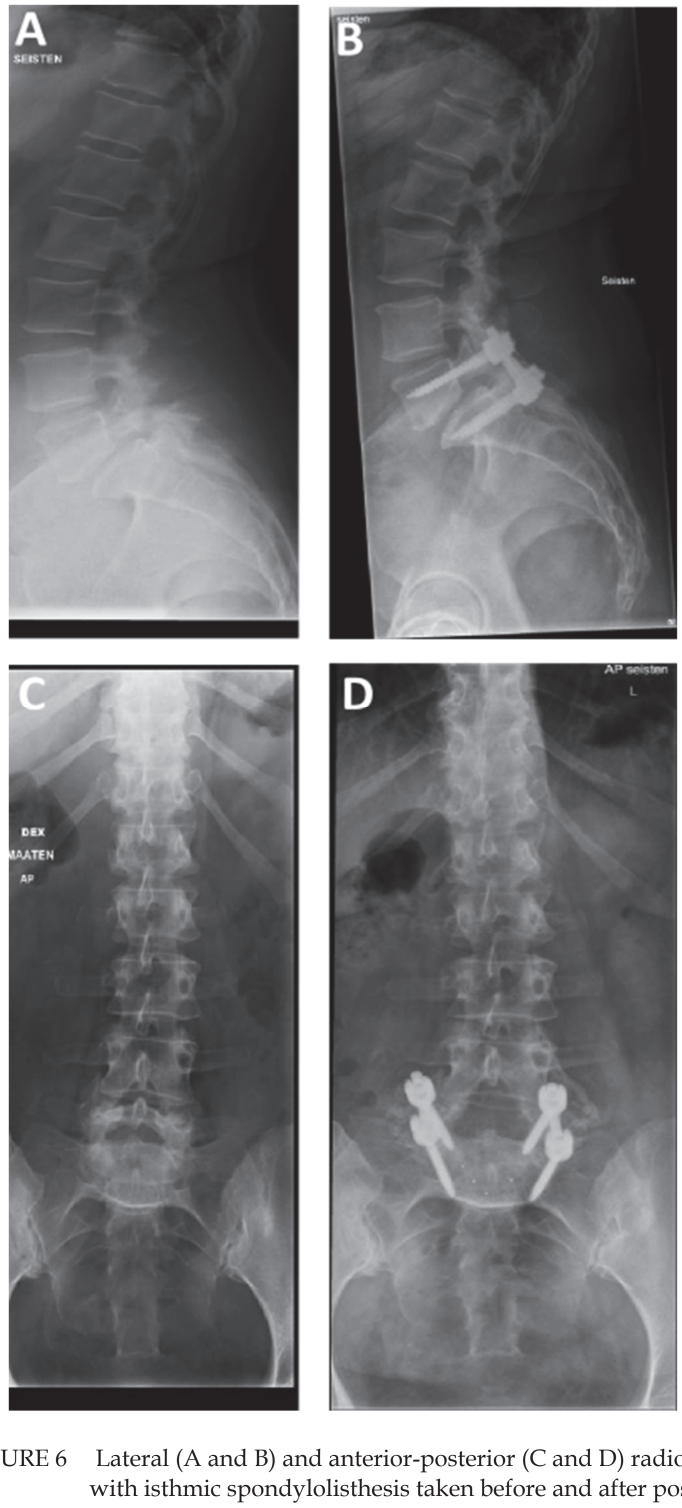


FIGURE 6 Lateral (A and B) and anterior-posterior (C and D) radiographs of a patient with isthmic spondylolisthesis taken before and after posterolateral fusion and TLIF. X-rays from Tampere University Hospital.

2.3.1 The effect of fusion on trunk muscles, spinal mobility and degeneration of the lumbar spine

LSF-related research has mainly focused on operating techniques. The trunk muscle strength of LSF patients have been compared with that healthy subjects or conservatively treated patients in only two studies. In their cross-sectional study, Tiusanen et al. (1996) compared the isokinetic trunk extension and flexion strength levels of patients, at an average of 5.2 years after anterior interbody lumbar fusion, with those of healthy controls. The patients' values were clearly lower than those in the healthy subjects. In the follow-up study by Keller et al. (2004), isokinetic trunk extensor muscle strength and isometric endurance were compared between patients randomized into a lumbar fusion group and a cognitive intervention and exercise group (muscle strength, endurance, and coordination training). In the lumbar fusion group, extensor muscle strength and endurance were lower at the 1-year follow-up than baseline values. In the conservatively treated group, muscle strength increased and muscle endurance remained unchanged. The researchers noticed a decrease of about 20% in isokinetic trunk extension strength from the preoperative level during a 1-year follow-up in the fusion group. However, in their 9-year follow-up study the difference in trunk muscle strength between the two groups had disappeared, but trunk extensor-flexor imbalance remained observable in both groups (Froholdt et al. 2011).

Multifidus muscle atrophy (Kim et al. 2005, Fan et al. 2010a, Fan et al. 2010b) and fatty infiltration (Fan et al. 2010b) have been observed in magnetic resonance imaging (MRI) studies in LSF patients. Changes in the cross-sectional area of the LM are larger in the conventional open approach than mini-invasive approach (Kim et al. 2005, Fan et al. 2010a, Fan et al. 2010b). If paraspinal muscle damage is minimized by using a mini-invasive technique, this may have positive effects on postoperative trunk extensor muscle performance (Kim et al. 2005). Muscle atrophy was also associated with postoperative pain and disability after a one-year follow-up (Fan et al. 2010a).

Decreased trunk extension strength and muscle atrophy may be a consequence of paraspinal muscle injury during posterior LSF. The factors responsible for such injury are: (i) dissection and disruption of LM tendinous attachments from the spinous process, which may destroy internal vasculature and tissue structure, (ii) the use of electrocautery, and (iii) the use of self-retaining retractors, which increase intramuscular pressure and impede local blood flow, further causing acute ischemic necrosis. The LM is also especially vulnerable to denervation due to its monosegmental innervation pattern (Kim 2010, Hu, Fang & Fan 2013).

Reducing the number of mobile lumbar segments alters the biomechanical behaviour of the adjacent motion segments. In a 24-month follow-up study, monosegmental fusion did not significantly change the total lumbar range of motion but increased the motion of the adjacent segment, if the fused segment was L5-S1. L5-S1 fusion also increased the contribution of L4-5 to the total lumbar range of movement (Auerbach et al. 2009). In another study, L4-5 fusion increased relative movement of both the cranial and caudal segments (Morishita et al. 2011). Lumbar and lumbosacral fusions may also affect the loading on the sacroiliac joint (Yoshihara 2012).

Spinal fusion is assumed to increase load at levels adjacent to the fused segments, which in combination with underlying natural degeneration, lead later to adjacent level instability and degeneration (Gillet 2003, Helgeson, Bevevino & Hilibrand 2013). Age above 60 years, pre-existing facet degeneration and/or disc disease, multilevel fusion, stopping at construct L5, performing a laminectomy adjacent to a fusion, and excessive disc height distraction during posterior interbody fusion predispose a patient to the development of adjacent segment pathology (Lawrence et al. 2012). Sacroiliac joint degeneration develops more frequently in patients undergoing lumbosacral fusion regardless of the number of fused segments. Sacroiliac joint degeneration may also be a consequence of iatrogenic injury during posterior iliac bone harvesting (Ha, Lee & Kim 2008).

The evidence on the effect of fusion on degeneration when compared to non-fusion patients is controversial. Froholdt et al. (2013) found no difference in lumbar disc degeneration in subjects randomised into an instrumented lumbar fusion or conservative treatment group after a 9-year follow-up, whereas Ekman et al. (2009) in a 12-year follow up, reported that fusion accelerated degenerative changes at the adjacent level compared with natural history, although the clinical importance of degeneration seemed limited. The role of postoperative changes in disc height in explaining postoperative pain and disability is unpredictable and indefinite (Gillet 2003).

2.3.2 The effectiveness of lumbar spinal fusion compared to conservative treatment

LSF rates have risen during recent decades, although conclusive evidence of the effectiveness of the operation is lacking (Harris & Dao 2009, Rajaee et al. 2012). The effectiveness of lumbar fusion with non-operative treatment has been compared in six separate randomized controlled trials (RCT) (Fritzell et al. 2001, Brox et al. 2003, Fairbank et al. 2005, Brox et al. 2006, Ekman et al. 2009, Ohtori et al. 2011). Exercise was a central component of non-operative treatment in all these RCT studies (Table 3). In four RCTs, disability decreased significantly more in the fusion than conservative treatment group at the 2-year follow-up. However, the benefit of LSF seems to disappear over the long term (Ekman, Moller & Hedlund 2005, Mannion, Brox & Fairbank 2013). According to the latest systematic reviews, fusion surgery can be considered for CLBP due to degenerative disc disease and with or without isthmic spondylolisthesis, if multidisciplinary rehabilitation has failed to improve the patient’s condition (Wood et al. 2011, Phillips et al. 2013). However, comparison between fusion and nonsurgical treatment of CLBP is problematic, as clinical practice, surgery is typically performed only after the failure of non-operative treatment, and thus they are not parallel treatments (Phillips et al. 2013).

TABLE 3 Randomized controlled trials comparing lumbar spine fusion with conservative treatment.

Study	Subjects, Diagnosis	Interventions	Main outcome and Length of Follow-up	Main Results
Moller & Hedlund 2000, Ekman, Moller & Hedlund 2005	n=111 F=54, M=57 G1: n= 77, G2: n= 34, mean age 39 y Isthmic spondylolisthesis	G1: Posterolateral fusion with or without instrumentation G2: Exercise program (strength and postural training with emphasis on abdominal and back muscles) 3 session per week for the first 6 months and 2 session per week between 6 and 12 months	Disability Pain 2, 9 (range 5-13), and 10 (range 10-17) y	Disability and pain decreased significantly more in fusion group at 2 years No significant differences between groups in long-term follow-up.
Fritzell et al. 2001	n=294 G1: n=221, F=112, M=110, mean age 43 y G2: n=72, F= 35, M=37, mean age 44 y CLBP with degenerative disc disease	G1: Instrumented or noninstrumented posterolateral fusion or instrumented circumferential fusion G2: Physical therapy with other forms of treatment (information and education, treatment aimed at pain relief, cognitive and functional training, and coping strategies)	Disability Pain Depression scale 24 mo	All outcome measures except depression scale improved significantly more in fusion group
Brox et al. 2003	n=64 G1: F=22, M= 15, mean age 44 y G2: F= 18, M=9, mean age 42 y CLBP with degenerative disc disease	G1: Lumbar fusion with posterior transpedicular screws and standardized advice for the first 3 months G2: Cognitive intervention and exercises (muscle endurance and coordination training, cocontraction of the deep abdominal muscles and lumbar multifidus). Supervised treatment for 1 week, then 2 weeks at home and 2 weeks under supervision	Disability 12 mo	No significant differences between groups in disability.
Brox et al. 2006	n=60 G1: n=29, F=18, M=11, mean age 42 y G2: n= 31, F= 11, M=20,	G1: Posterolateral fusion with transpedicular screws, advice on physical activities, and follow-up consultations at 3 and 6 months G2: As in Brox et al. 2006	Disability 12 mo	No significant difference in treatment effect between groups

	mean age 43 CLBP and previous surgery for disc herniation			
Froholdt et al. 2012	Data combined from Brox et al. 2003 & 2006		Disability 9-years	No significant difference between groups
Fairbank et al. 2005	n= 349 G1: n=176, F=97, M=79 G2: n= 173, F=80, M=93, mean age not reported CLBP	G1: Flexible stabilization or fusion with technique left to discretion of operating surgeon. G2: Intensive rehabilitation (stretching, flexibility exercises, muscle strengthening, spine stabilization exercises, and aerobic training) program with principles of cognitive behavior therapy. 5 days per week for 3 weeks. Follow-up sessions at 1, 3, 6, and 12 months after treatment.	Disability Shuttle walking test 6, 12, and 24 mo	Disability decreased significantly more in fusion compared to rehabilitation group at 24 mo follow-up
Ohtori et al. 2011	n=41 G1: n= 20, F=10, M=10, mean age=33 G2: n= 15, F=10, M=5, mean age 35 G3: n= 6, F= 4, M=2, age 37 Discogenic low back pain patients	G1:Exercise treatment (daily walking and stretching during 2 years) G2: Anterior interbody fusion G3: Posterolateral fusion with pedicle screws	Pain Disability Clinical symptoms score 2-years	Pain, disability and clinical symptoms score improved significantly more in both fusion group than in exercise group
Mannion, Brox & Fairbank 2013	Data combined from Brox et al. 2003 & 2006 and Fairbank et al. n= 473, F= 246, M= 227, mean age 41y	Described in Brox et al. 2003 & 2006 and Fairbank et al. 2005	Disability 11.4 (range 8-15) y 55% of patients completed follow-up	No difference between groups in disability

F= Female, M= Male, G= Group

2.4 Postoperative rehabilitation after lumbar spinal fusion

Decrease in pain and disability and improved quality of life are the main post-operative aims in LSF patients. Attempts to achieve these aims are made via improving both functional capacity of the lumbo-pelvic complex and health-related fitness. LSF patients may have been inactive for a prolonged period before surgery owing to pain. Consequently, a patient with impaired physical ability cannot be physically active enough to maintain or improve muscular and cardiovascular capacity. Further, the patients who have undergone LSF are concerned about ensuring that the fusion heals as intended. For this reason, many patients are afraid to be active, fearing that they will jeopardize the fusion process. Thus although persons undergoing LSF surgery need more specific and intensive trunk and total body muscle training, is important not to forget other areas of health-related fitness that have positive effects on work ability and quality of life in addition to improved physical functioning. Currently, information on what post-operative therapeutic exercise should include is minimal.

2.4.1 Selection of exercises for rehabilitation program after lumbar spinal fusion

Several factors need to be taken into account in the planning of a LSF postoperative exercise program. First, patients undergoing a LSF operation will be chronic highly disabled pain patients (Pekkanen et al. 2013a). Thus, several structural and functional changes may have taken place in their trunk muscles and spinal control that will not spontaneously normalize after surgery, although the intensity of pain will probably decreases. Secondly, fusion itself changes the normal biomechanics of the lumbar spine, and causes muscle injury and atrophy which especially affect adjacent segment function. Thirdly, healing of soft tissue and bone, limit loading of the spine during the early recover. It takes several months before bony fusion achieves adequate strength (Kalfas 2001, Pilitsis, Lucas & Rengachary 2002). Strain on the fused and adjacent segment and risk of breakage of the instrumentation or pulling out of the pedicle screws should also be minimized during rehabilitation (Christensen 2004). It is challenging to find exercises for a rehabilitation program that are simultaneously safe, functional to maximize transfer of the training effect to daily activities, and fulfil the demands of training intensity.

Trunk stability can be seen as the product of central nervous system function and the muscular capacity of the lumbo-pelvic complex. Trunk strength and endurance are critical for performance because all movements either originate in or are coupled through the trunk (Kibler, Press & Sciascia 2006, Okada, Huxel & Nesser 2011). Deficiencies in central nervous system function or muscle capacity decrease the ability to prevent trunk torque, which results in uncontrollable motion and injury (Zazulak, Cholewicki & Reeves 2008).

The neutral lumbar spine position has been defined as the position of the spine during natural upright posture or as the midrange position between end-range flexion and extension and slight lumbar lordosis (with relaxed thorax) in the sitting posture (O'Sullivan et al. 2003, O'Sullivan et al. 2013, Pavlova et al. 2014). Maintaining the neutral position of the lumbar spine during loading increases the shear and compression tolerance of the spine and probably improves the safety of the exercises (McGill, Hughson & Parks 2000, Gunning, Callaghan & McGill 2001). The term functional neutral spine control exercise is a descriptive term for exercises which aim to improve both the capacity of control of the neutral spine position and position sense awareness (Akuthota & Nadler 2004). During neutral spine control exercise, a destabilizing force acts on the trunk via loading of the extremities, and therefore proper recruitment of the trunk muscles is required to stabilize the lumbar spine and pelvis (McGill et al. 2009). Trunk muscle strength and endurance are important both for functional capacity and for optimal function of the lumbo-pelvic complex (Wagner et al. 2005). Neutral spine control exercises have been reported to decrease pain in patients with chronic low-back pain (Suni et al. 2006).

Martuscello et al. (2013) classifies trunk muscle exercises into the categories. 1) Core stability exercises are low-load exercises, which aim to isolate specific trunk muscles and improve their neuromuscular control. 2) Traditional core exercises are low-load dynamically performed floor exercises that focus on the superficial trunk muscles. 3) Ball/device exercises are performed with the addition of equipment and aim at increasing core muscle activity. 4) Squats, deadlifts, and lunges are free weight exercises which require the trunk muscles to work to stabilize and support the movement of the weight. 5) Non-core exercises, such as the cable chest-press and shoulder-press, are performed to activate muscles distal to the core, but also simultaneously provide core activation. In this classification, neutral spine control exercises are in the category of non-core exercises. If performed in the standing position, both free weight and non-core exercises can be seen as functional exercises, since activation of the trunk muscles during those exercises mimic specific trunk muscle function patterns needed in performing occupational and functional daily tasks (Borghuis, Hof & Lemmink 2008). Thus, the transfer effect of functional training for real life demands may be better than e.g. that of traditional core exercises.

Resistance training of the trunk muscles aims to achieve structural, neural, and metabolic changes in order to improve functional and structural deficiencies related to CLBP and LSF. With the selection of correct and appropriate exercise, it is possible to focus changes on the desired muscles and functions. In order to achieve a training effect, exercises intensity should be challenging enough. To achieve changes in muscle endurance characteristics, a sufficiently high level of resistance for the designed exercises should be 40-60% of the 1 repetition maximum (RM). Similarly, for the improvement of muscle strength and hypertrophy, the resistance level should be 60-70% and 70-85% of the 1RM, respectively (American College of Sports Medicine 2009). However, the RM method cannot be used in the evaluation of trunk muscle loading during neutral spine control exercises, because the loading happens via movement of the extremities.

Surface electromyography (EMG) is a widely used non-invasive technique to analyse the level of trunk muscle activity during rehabilitation and strength training exercises. The amplitude of the EMG signal can be reported as a raw value (in millivolts) or as a normalized value as the percentage of maximum voluntary isometric contraction (% of MVIC). Normalized EMG data provide an estimation of the level of neuromuscular effort, while normalization also allows direct quantitative comparison of EMG findings between subjects (Lehman & McGill 1999). EMG can be used as an indicator of the intensity of neutral spine control exercises, since a linear relationship between isometric trunk muscle force and EMG amplitude has been reported (Brown & McGill 2008a). Exercises that elicit larger activity represent greater challenges to the neuromuscular system. It can be assumed that EMG activity of at least 60% of MVC is required to obtain the desired physiological adaptations in terms of efficient strength gain, neural adaptations, and muscle fibre hypertrophy (Andersen et al. 2006).

Several studies have reported trunk muscle EMG activity during functional neutral spine control exercises, where loading happens via upper limb movement (Table 4). Direct comparison of results between different studies is difficult due to different loading protocols, measurement approaches, and equipment. In addition, subjects are usually healthy young people (Arokoski et al. 2001, Behm et al. 2005, Fenwick, Brown & McGill 2009, Marshall, Desai & Robbins 2011). However, on the basis of results of previous studies, it seem that it is challenging to achieve trunk muscle activity level that is sufficient (>60% of MVC) to lead to improved muscle strength during neutral spine control exercises. On the other hand, there are several exercises by which it is possible to achieve a sufficient muscle endurance training level (40-60% of MVC) with submaximal resistance (Table 4).

TABLE 4 Electromyographic activation during upper limb exercises.

Study	Subjects	Exercise, resistance, and studied muscles, and/or spinal level of measurement	Main Results
Arokoski et al. 2001	N= 24 healthy subjects, F=14, M= 10 age range 21 - 39 y	Bilateral isometric shoulder extension and flexion and unilateral horizontal adduction. Manual resistance. Bilaterally RA, OEA, longissimus and multifidus.	Shoulder extension activate RA and OEA at level which was > 50% of MVC in women Activity of longissimus and multifidus was ≥ 50% of MVC during shoulder flexion in women and men
Behm et al. 2005	N=11 healthy subjects, F=5, M=6, mean age 24 y	Unilateral shoulder press For male 13.6kg dumbbell and for female 6.8 kg OIA, upper and lumbosacral ES.	Unilateral shoulder press caused greater activation of the back muscles when compared with bilateral presses. No exact % of MVC values reported.
Lett & McGill 2006	M=9	Bilateral shoulder height and waist height pull and push 400.5 N RA, OIA, OEA, ES T9, ES L3, ES L5	Shoulder height push produced the largest muscle activation ant it was measured in OIA, 44 % of MVC
Santana, Vera-Garcia & McGill 2007	M=14 healthy subjects, mean age 28 y	Unilateraalinen horisontaalinen adduction 1 RM RA, OIA, OEA, ES T9, ES L3, ES L5	Muscle activation level over 60% of MVC was measured in OIA
McGill et al. 2009	M=8 mean age	Cable walk out (mean load 5.4 kg), overhead cable push (mean	The highest activation was measured in OIA during cable walk out, mean activation level remained <50% of MVC

	22 y	load 5.2kg) RA, OIA, OEA, ES T9, ES L3	
Fenwick, Brown & McGill 2009	M=7, healthy subjects, mean age 27 y	1-armed cable row 50% of load used in inverted row exercise RA, OIA, OEA, ES T9, ES L3	The highest activation was measured in upper ES, mean activation level remained <50% of MVC
Marshall, Desai & Robbins 2011	N=20 10 CLBP patients, F=5, M=5, mean age 34 y 10 healthy subjects, F=5, M= 5, mean age 33 y	Bilateral shoulder flexion 60% of 1 RM RA, OEA, ES L4/5	Mean activity level of ES was >50% of MVC in both study groups
Youdas et al. 2012	N=25 F=13, healthy subjects, mean age 25 y M=12, mean age 26 y	Unilateral abduction 10RM OEA, ES	Mean activity level remained under 30 % of MVC
Saeterbakken & Fimland 2012	M=15, healthy subjects, mean age	Bilateral and unilateral shoulder press in standing and seated position 60% of 1RM	Abdominal muscle activity was higher during unilateral than bilateral press and higher during standing than seated position. ES activity was higher during unilateral than bilateral press in standing position. No exact % of MVC-values reported.

	22 y	RA, OEA, ES L1	
Parry, Straub & Cipriani 2012	M=11, healthy subjects, age range 19-32 y	Unilateral abduction and flexion 4.5 kg dumbbell ES L3	ES activity during unilateral shoulder flexion was >50% of MVC

F= Female, M= Male, RM= Repetition maximum , MVC= Maximal voluntary contraction, RA = Rectus abdominis, OIA= Obliquus internus abdominis, OEA= Obliquus externus abdominis, ES= Erector spinae, T= Thoracic, and L= Lumbar

2.4.2 Effectiveness of postoperative rehabilitation

The effectiveness of exercise therapy after LSF has been evaluated in five RCTs (Table 5). In these studies, the timing of the interventions differed. In the studies of Nielsen et al. (2008, 2010), rehabilitation started 6 to 8 weeks before surgery and continued during hospitalization. Abbott et al. (2010) evaluated the effectiveness of psychomotor therapy implemented during the first 12 postoperative weeks. In the study of Monticone et al. (2014), cognitive-behavioural therapy continued during the first four postoperative weeks. In the first study, the Danish research group compared three different postoperative rehabilitation programs lasting between 12 and 20 postoperative weeks, and later the same group evaluated the impact of initiating rehabilitation either 6 or 12 weeks after LSF (Christensen, Laurberg & Bunger 2003, Oestergaard et al. 2012).

Exercise was an essential component of the rehabilitation protocols in all the RCT studies; however the guidance and exercise methods used were different. In Nielsen et al. (2008) and Christensen et al. (2003), the exercise programs included muscle endurance and strength training for the trunk muscles, and cardiovascular conditioning. In Abbott et al. (2010) and Monticone et al. (2014), the exercise program consisted of motor relearning training of the trunk muscles. Cognitive-behavioral elements related to fear of movement or injury were also an essential part of the program.

The results of these studies indicate that while exercise therapy has a role in decreasing pain and disability in LSF patients, including cognitive-behavioural elements in the therapy may further increase the effect of postoperative rehabilitation. However, the best practice in postoperative rehabilitation remains unclear (Rushton et al. 2012).

TABLE 5 Randomized controlled trials on postoperative rehabilitation after lumbar spine fusion.

Study	Subjects, Diagnosis, Operation technique	Intervention, Timing	Outcome and length of follow-up	Main Results
Christensen, Laurberg & Bunger 2003	n=90, F=60, M=30, age 45 G1: n=30 G2: n=30 G3: n=30 Isthmic spondulolisthesis, primary degeneration, secondary degeneration + Posterolateral or circumferential fusion	G1: video of the exercises (back, abdominal, and leg muscle endurance), one instruction session G2: Same program as G1, in addition 3 meetings with PT and other fusion patients during 8 weeks G3: 2 x/week training session (conditioning training, muscle endurance training, and stretching exercises) lasting 8 weeks under the supervision of the PT Commencement of the interventions: 3 months after the surgery	Back and leg pain Daily function Work status Use of Back-related health care 3, 6, 12, and 24 months after surgery	At the 2 y follow-up: Non-significant difference between groups in back pain score G1 and G2 scored significantly lower leg pain than G3 More patients resumed work in G2 and scored higher in daily function Health care use was significantly higher in G1 than in G2 or G3.
Nielsen et al. 2008, Nielsen et al. 2010	n=60 G1: n= 32, F=19, M=13, age 52 y G2: n=28, F=17, M=11, age 48 y Degenerative lumbar disease + uninstrumented fusion, instrumented fusion, or disc prosthesis	G1: Usual care G2: Combined preoperative training (muscle strength training for the back and abdomen and cardiovascular conditioning), presurgical information, patient-controlled epidural analgesia, and intensive postoperative mobilization.	Postoperative stay Complications Functionality Pain Satisfaction health related quality of life Costs 1, 3 and 6 months	Postoperative stay was shorter in G2 and G2 was less costly than G1 Patients in G2 experienced significantly less pain and more patients in G2 were very satisfied with the overall treatment and outcome than in G1. No significant difference between groups in other outcome measures.

Abbott, Tyni-Lenne & Hedlund 2010	n= 107 G1: n=54, F=31, M=18, age 50 y G2: n=53, F=35, M=23, age 51 y Spinal stenosis, spondylosis, degenerative or isthmic spondylolisthesis or degenerative disc disease	G1: Home training program (Back, abdominal, and leg muscle endurance training, stretches and cardiovascular training G2: 3 outpatient sessions focusing on modifying maladaptive pain cognitions, behaviours, and motor control of transversus abdominis and multifidus. Home motor control training program	Disability Back pain HRQL Outcome expectancy Self-efficacy Fear of movement/injury Coping 3, 6, 12 months and 2- to 3 years	Scores for disability, self-efficacy, outcome expectancy and fear of movement improved significantly more in G2 than in G1 at all follow-up points.
Oestergaard et al. 2012	n=82 G1: F=20, M=21, age 52 y G2: F=24, M=17, age 51 y Dg: degenerative disc disease, spondylolisthesis + instrumented lumbar spinal fusion	4 x 2-hour meetings with PT and other fusion patients: exchange of experiences, guidance for home exercises, and instructions in proper ergonomics and working postures G1: commencement of intervention 6 weeks after surgery G2: commencement of intervention 12 weeks after the surgery	Disability 6 weeks and 3, 6, and 12 months after surgery	Decrease in ODI was significantly lower in G1 compared to G2 at the 6- and 12-month follow-up.
Monticone et al. 2014	n=130 G1: F=44, M= 21, age 59 y G2: F=35, M= 30, age 56 y Dg: degenerative or isthmic spondylolisthesis, CLBP and/or sciatica and unresponsive to conservative treatment + lumbar fusion with or without decompression	G1: Cognitive-behavioral therapy 2x/week during 4 weeks aiming to modify catastrophizing and fear of movement + exercise program: spine mobilization and functional exercises aiming to improve motor control of the spine and walking program and ergonomic advices G2: Exercise program as in G1	Disability 12 months	Disability decreased significantly more in G1 than in G2

F= Female, M= Male, G= Group, HRQL= health-related quality of life

3 PURPOSE OF THE STUDY

The purpose of this research project was to develop an evidence-based training program for postoperative rehabilitation after lumbar spine fusion. The main focus was to test the feasibility of neutral spine control exercises for rehabilitation purposes. The detailed objectives of this research were:

1. To determine pain, disability, trunk muscle strength, and functional mobility pre- and postoperatively in patients undergoing lumbar spine fusion and to analyze associations between changes in trunk muscle strength and disability (Study I).

2. To assess abdominal and back muscle activity during functional isometric and dynamic pushing and pulling exercises in healthy subjects (Study II, III) and, in addition, to evaluate the effect of pelvic fixation during exercise on trunk muscle activity.

3. To evaluate trunk muscle activity and intensity of pain during neutral spine control exercise in LSF patients (Study IV).

4. To develop a trunk muscle training program for postoperative rehabilitation in LSF patients to be implemented in a randomized controlled trial (Study V).

4 MATERIAL AND METHODS

4.1 Subjects

The study population comprised of both healthy subjects and LSF patients. In the study I, 114 patients (64% females and 36% males), who had undergone non-urgent lumbar spine fusion, owing to degenerative olisthesis, spondylolysis, lumbar spinal stenosis, or degenerative disc disease, in Tampere University Hospital and Central Finland Central Hospital participated in the study. The study inclusion period was between January 1, 2008, and August 31, 2009. Patients were excluded from the study if any outcome variable was missing. The mean (SD) age of the patients was 60 (12) years (range, 29–85 years). The median (IQR) duration of low back pain before the operation was 36 (18–84) months.

In studies II and III, 20 healthy women aged from 20 to 45 years constituted the study population. All subjects were recruited through an advertisement in the Jyväskylä Central Hospital newsletter. Exclusion criteria were a neurologic, orthopedic, or cardiorespiratory problem (injury/disease) which prevented maximal exertion in the strength measurements. Subjects were also excluded if they were pregnant, had a body mass index (BMI) of >25, or if they were competitive athletes.

In the third cross-sectional study, the patient group comprised 11 men and 11 women aged from 25 to 84 years. All patients had undergone non-urgent instrumented LSF in Tampere University hospital 3 to 11 months before the measurements. The diagnoses for elective spinal fusion were degenerative olisthesis (n=13), spondylolysis (n=7), lumbar spinal stenosis (n=1), and degenerative disc disease (n=1). Patients were excluded if they were under age 20, had a BMI 30 or more, or if they had a neurologic, orthopedic, or cardiorespiratory problem which would prevent their engagement in the type of physical exertion required in the study.

The main surgical principles and pre- and postoperative rehabilitation were similar in both study hospitals (Study I and IV). All measurements were performed in the biomechanics laboratory of the Department of Physical Medicine and Rehabilitation in Central Finland Central Hospital or in the biomechanics laboratory of the Department of Physical Medicine and Rehabilitation in Tampere University Hospital.

The surgical procedure used was instrumented posterolateral fusion (PLF) with or without posterior lumbar interbody fusion. In general, in the PLF procedure using the midline incision, muscles are detached from the spine and retracted during the operation. Transpedicular fixation is placed between the fused segments. Decompression is performed, if needed, to relieve compression of nerve roots. If posterolateral fusion is thought to be insufficient or if indirect foraminal decompression is needed, additional interbody fusion is performed using PLIF or TLIF cages and bone transplant. Transverse processes are decorticated and either an autograft from the iliac crest, removed lamina and allograft bone, or bone substitute is placed bilaterally.

Preoperatively, patients met the spine surgeon, anesthesiologist, and physiotherapist, and received information about the operation and rehabilitation. The early postoperative mobilization of the patients in the orthopaedic ward was carried out by a physiotherapist.

After hospitalization, patients were instructed to sit a maximum of one-half hour continuously during the first 4 weeks, and to avoid extreme bending of the trunk and not to lift items that weighed more than 5 kilograms for 2 months postoperatively. Use of a bicycle ergometer was allowed one month, and other exercises, such as, skiing, dancing, and water gymnastics, two months after the operation. During the early recovery stage, patients were instructed to walk and perform light abdominal, back, and thigh muscle exercises, and stretches for the hip, knee and ankle muscles every second day. The number of repetitions per set was increased gradually from 5-10 up to 30. After the first postoperative guidance session 6 weeks postoperatively, trunk muscle endurance exercises were added to the home exercise program. More strenuous loading of the lumbar spine and a gradual return to normal activities were allowed after the 3-month control visit.

Subjects in all studies were informed of the study protocol and possible risks and discomfort related to the measurements, and signed an informed consent form before participation. The study protocols were approved by the Ethical Committees of the Central Finland Central Hospital and Tampere University Hospital.

4.2 Study design

Study I was a prospective follow-up study, and studies II, III and IV were cross-sectional studies. Study I was carried out to evaluate the changes in trunk muscle function pre- and postoperatively in LSF patients. In studies II and III trunk muscle activation during upper limb exercises was measured with maximal resistance and with and without pelvis fixation in healthy subjects. In the study IV, NSC exercises were tested with a 10-RM resistance in postoperative patients.

The results of these studies were utilized in the development of the postoperative rehabilitation protocol (V) (Figure 7).

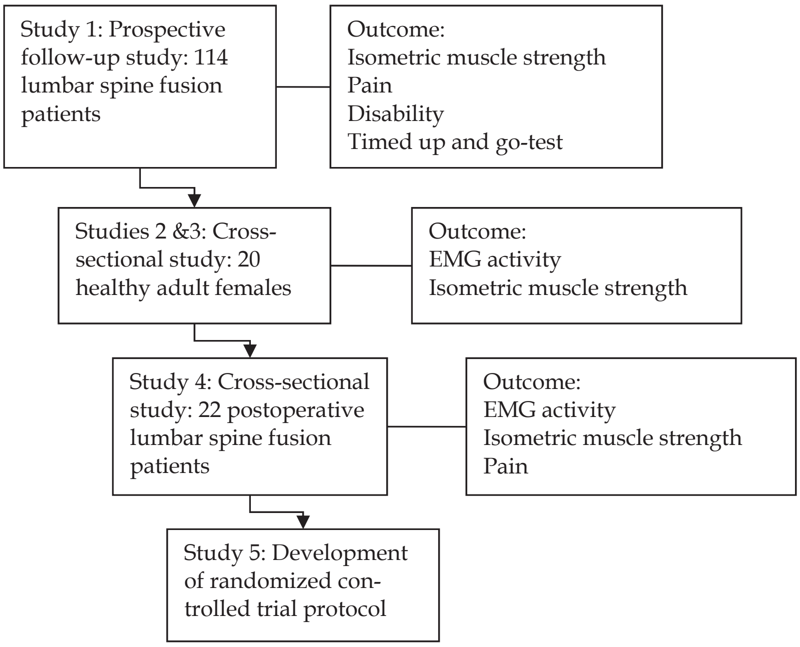


FIGURE 7 Overview of the study design.

4.3 Measurements

4.3.1 Isometric trunk muscle strength

Isometric trunk muscle extension, flexion (studies I, II, III, and IV), and lateral flexion (II and III) strength were measured using a strain-gauge dynamometer (DS Europe, Milano, Italy). The strength measurements were performed in a standing position (Rantanen, Airaksinen & Penttinen 1994, Paalanne et al. 2009) in a strength measurement apparatus (Figure 8). During the measurement, the pelvis was supported at the level of the greater trochanter (II and III) or the anterior superior iliac spine (I and IV). Lower limbs were supported at the midpoint of the thighs (II and III) or below the knees (I and IV). The feet were positioned 20 cm apart. A harness was fastened around the upper body at the level of the shoulders, and this was horizontally attached to a strain-gauge dynamometer. Isometric trunk lateral flexion (right and left) was performed using the same measurement apparatus. During the measurement, the subject was positioned sideways in relation to the measuring frame so that the shoulder was against the cushioned plate attached to the dynamometer.

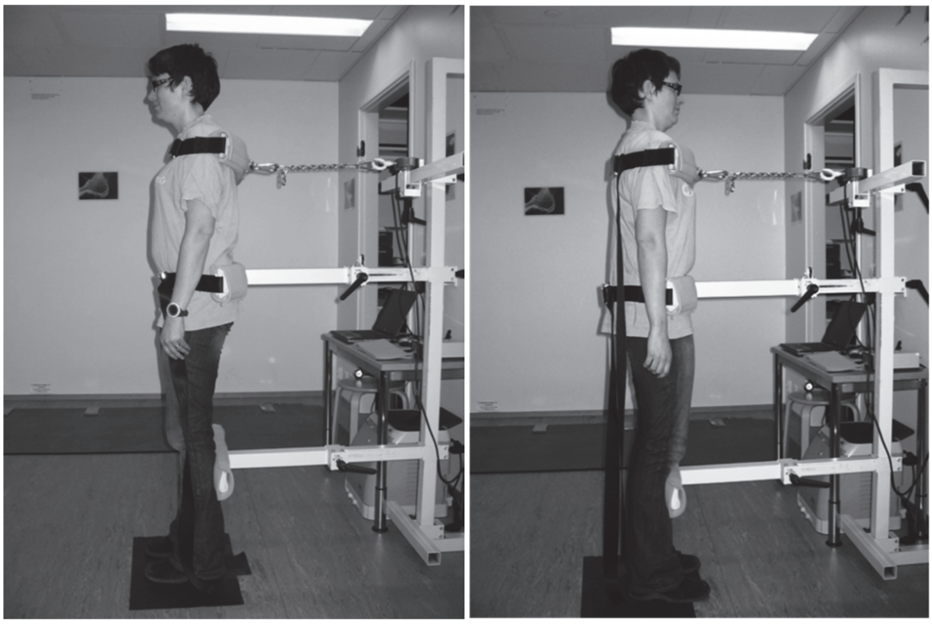


FIGURE 8 Measuring maximal isometric trunk flexion (left) and extension strength (right).

In the trunk strength measurements, the subjects performed the tests with maximal effort for approximately 5 seconds. Two maximal efforts were performed. If the measured strength level showed an increase of more than 10% from the first effort, an additional effort was performed. The best result was used in the analysis. Both the intra- and inter-rater reliability of isometric trunk strength tests in the standing position has been indicated to be good, with ICC values ranging from 0.87 to 0.95 (Hutten & Hermens 1997, Paalanne et al. 2009).

4.3.2 Surface electromyography

Electromyography activity of trunk muscles was measured with an eight-channel bipolar surface EMG recorder (ME3000P8 in studies II and III, and ME6000 in study IV) (Mega Electronics Ltd, Kuopio, Finland). Raw EMG data were recorded using a sampling frequency of 1000 Hz. The EMG signal was changed into digital format and saved on a computer for analysis. The raw EMG signal was rectified and averaged. The average amplitude level (μV) of every exercise was calculated as the average of each of the data segments (100ms) of the analysis period. A time period of four (II) or three (IV) seconds was selected for analysis at the point where the electrical activity level was at its greatest during each isometric exercise. The starting and finishing points of the dynamic upper limb exercises were determined from simultaneous electromyographic and video (DCR-HC96E, Sony, Japan (II) and Legria HV40, Canon, Japan (IV)) analysis, and the whole period was used for analysis (III). In study IV, the fifth repetition of the set was selected for analysis. The performance was divided into eccentric and concentric phases and each analyzed separately.

In studies II, III, and IV, subjects participated in two test occasions. During the first session, the heights of the isometric strength measurement frame and the pelvis and lower limb fixation frame were adjusted individually for each subject and they were given an opportunity to practice the studied exercises in order to learn the proper performance technique. In studies III and IV, the loads to be used during the dynamic 1-RM (III) and 10-RM (IV) exercises were evaluated individually. In defining the resistance, the load was added to the weight stack system of a pull machine (544, Frapp, Joensuu, Finland (III), Lojer Ltd., Sastamala, Finland IV) and subjects attempted 1 (III) or 10 (IV) repetitions with the proper performance technique. After each successful repetition/set, the weight was increased until the subject could no longer complete 1 or 10 repetitions.

The second test occasion began with the attachment of the electrodes. Silver/silver chloride surface electrodes (M-00-S, Medicotest Inc, Ölstykke, Denmark) were used in the measurements. The skin at the electrode attachment sites was shaved, cleaned with sand paper and then wiped with alcohol in order to decrease skin impedance. Electrode pairs were positioned on both sides of the body on the following trunk muscles in the direction of the muscle fibres (De Foa, Forrest & Biedermann 1989, Hermens & Seniam 2000, Ng, Kippers & Richardson 1998): RA, 1 cm above the navel and 2 cm laterally from the midline; OEA, just below the curvature of the ribs; longissimus, 3 cm laterally from the L1 spinous process; and LM, 2 cm laterally from the L5 spinous process. The distance between the mid-points of the electrode pairs was 25 mm. The reference electrodes, to which a pre-amplifier was attached, were positioned in the area of the iliac spine. After attachment of the electrodes, a period of 10-15 minutes was allowed to pass before commencement of the measurements to ensure warming up of the electrode gel.

The reference exercises were performed first and then the other exercises. Both were performed in a random order. Abdominal muscle (rectus abdominis and external oblique) activities during maximal isometric trunk flexion and trunk extensor muscle (longissimus and multifidus) activity during maximal isometric trunk extension was used to normalize the activity levels collected during the actual exercises. The measurement method is described in the section on isometric trunk strength measurement. The muscle activity during the best result was used in the analysis. The relative loading of the trunk muscles was determined by comparing the ratio of EMG amplitude during the exercises to the amplitude elicited during maximal isometric voluntary contraction (% of MVIC) in the reference exercises.

The studied exercises were unilateral shoulder flexion and extension, unilateral shoulder horizontal adduction and abduction and bilateral shoulder extension and flexion, unilateral hip extension, and modified Roman chair (Table

6). In the exercises performed with the pelvis fixated, the pelvis was fixated to the measurement frame with a belt at the level of the greater trochanter. The upper limbs exercises in the standing position were performed with the lower limbs set in a striding position in which the heel of the left foot was in line with the toes of the right foot. The unilateral upper and lower extremity exercises were done only with the limb on right side.

Two maximal efforts of each of the isometric upper extremity exercises were performed and the effort with a higher strength value was chosen for analysis (II). In all studies, the subjects were advised to keep their lumbar spine in a neutral position during the performance of each exercise, thus ensuring that during the measurements the trunk muscle acted isometrically. The duration of each phase of dynamic upper or lower limb exercises was standardized by using a metronome at 50 (III) or 40 beeps per minute (3 s/repetition, 1,5 s concentric and 1,5 s eccentric) (IV).

TABLE 6 Description of studied exercises.

Exercise	Study	Performance position	Loading/resistance
1. Unilateral shoulder flexion	II and III	Standing with pelvis fixation	Maximal isometric (II), 1 RM (III)
2. Unilateral shoulder extension	II and III	Standing with pelvis fixation	Maximal isometric (II), 1 RM (III)
3. Unilateral shoulder horizontal adduction	II, III, and IV	Standing with (II, III) and without (III) pelvis fixation Sitting (IV)	Maximal isometric (II), 1 RM (III), 10 RM (IV)
4. Unilateral shoulder horizontal abduction	II, III and IV	Standing with (II, III) and without (III) pelvis fixation Sitting (IV)	Maximal isometric (II), 1 RM (III), 10 RM (IV)
5. Bilateral shoulder extension	II, III, and IV	Standing with (II, III) and without (IV) pelvis fixation	Maximal isometric (II), 1 RM (III), 10 RM (IV)
6. Bilateral shoulder flexion	IV	Standing without fixation	10 RM
7. Unilateral hip extension	IV	4-point kneeling position	Weight of lower limb
8. Modified Roman chair	IV	Biering-Sorensen test position	Weight of trunk

4.3.3 Disability and pain

The validated Finnish version of the Oswestry Disability Index (ODI) version 2.0 (Pekkanen et al. 2011) was used to evaluate disability due to back pain during the past week (scale 0–100) (I). Scores are defined on a scale according to the original publication; 0–20 as minimal, 20–40 as moderate, and 40–60 as severe disability. A score of 60–80 indicates a crippled patient, and 80–100 indicates that the patient is either bed-bound or exaggerating their symptoms (Fairbank et al. 1980). The intensity of back pain was assessed with the visual analogue scale (VAS), with participants ranking their pain on a scale of 0 (no pain) to 100 (worst possible pain) (Dixon & Bird 1981). Pain values were reported during rest and daily activities for the past week, during the trunk muscle strength measurements (I, IV), and during the measured exercises (IV).

4.3.4 Functional mobility

The Timed up and go (TUG) test was used to measure functional mobility (Podsiadlo & Richardson 1991). The TUG test is used to assess overall physical performance (power, walk velocity, agility and dynamic balance), and it has been shown to be a reliable and valid instrument to measure physical performance in low back pain patients (Simmonds et al. 1998). In the test the subject was asked to sit in a standard height chair. The subject was then asked to stand up, walk three meters to a mark on the floor, turn around, walk back to the chair, and sit down. The test began when the investigator said "go" and ended when the subject sat down. The time taken was recorded.

4.4 Statistical methods

Data were presented as means with standard deviations (SD) or 95% confidence intervals (CI), medians with inter-quartile ranges (IQR), or as counts with percentages.

Study I: Changes in outcomes were expressed with 95% CI and tested with paired samples t-test or permutation tests. Correlation coefficients were calculated using the Pearson method. The relationship between trunk muscle strength and ODI was analyzed using linear regression models.

Study II, III, and IV: Activity levels of each muscle were normalized by being expressed as a percent contribution of the activity during the reference exercises (% of MVIC). Repeated measures analysis of variance (ANOVA) was used to compare the surface EMG of each muscle, which was elicited during the different exercises. Paired t-tests were used to compare the force values and EMG activities of the different upper limb exercises, between the sides, and between the different exercise phases. The same tests were used to compare muscle activity with or without pelvis fixation (III). No adjustment was made for multiple testing, but this information can be obtained by multiplying the actual p-value by the number of comparisons made. The alpha level was set to $p< 0.05$ to determine statistical significance.

All statistical analyses were performed using the SPSS statistical software program (SPSS Inc, Chicago, IL, USA, Versions 12.0, 13.0, and 19.0).

5 RESULTS

5.1 Pain, disability, functional mobility and trunk muscle strength after LSF (Study I)

Preoperatively, the extension and flexion strength of the trunk muscles (SD) was 160 (95) N and 214 (101) N in females and 319 (198) N and 436 (221) N in males, respectively (Figure 9). In females, three months postoperatively, the extension and flexion strength of the trunk muscles increased by 24% and 18%, respectively, whereas in males the corresponding changes were minor (ns). Postoperatively, the strength of the trunk extensors and flexors were in females 29% and 36% and in males 36% and 55% of body weight.

Preoperative trunk extension/flexion strength ratio was 0.79 (0.34) in females and 0.76 (0.32) in males. Three months after surgery, the strength ratio had decreased to 0.66 (0.23) in males (p<0.05), whereas in females the ratio remained unchanged 0.82 (0.29) (p=0.38).

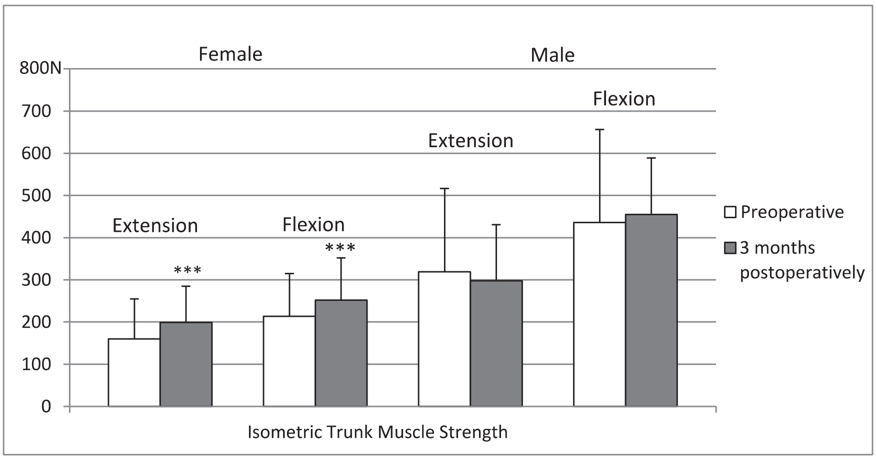


FIGURE 9 Isometric trunk muscle strength (*** p<0.001).

Preoperatively, mean (SD) back pain in females during rest was 37 (29) and during daily activities 66 (25). The corresponding values in males were 35 (27) and 65 (26). Three months postoperatively, rest pain had decreased by 77% in both sexes, and pain during activity by 65% in females and by 64% in males (all changes $p<0.001$). Intensities of back pain during the preoperative trunk extension and flexion strength measurements were 56 (31) and 42 (30) in females and 61 (27) and 46 (29) in males. Preoperatively, a small to moderate association between severity of pain during the strength test and the strength of the extensor ($r= -0.38$, 95%CI: -0.55 to -0.18) and flexor muscles ($r= -0.25$, 95%CI: -0.45 to -0.03) was observed in females, but not in males. Postoperatively, pain during the strength measurements was significantly lower compared to the preoperative values in both sexes ($p<0.001$) (Figure 10).

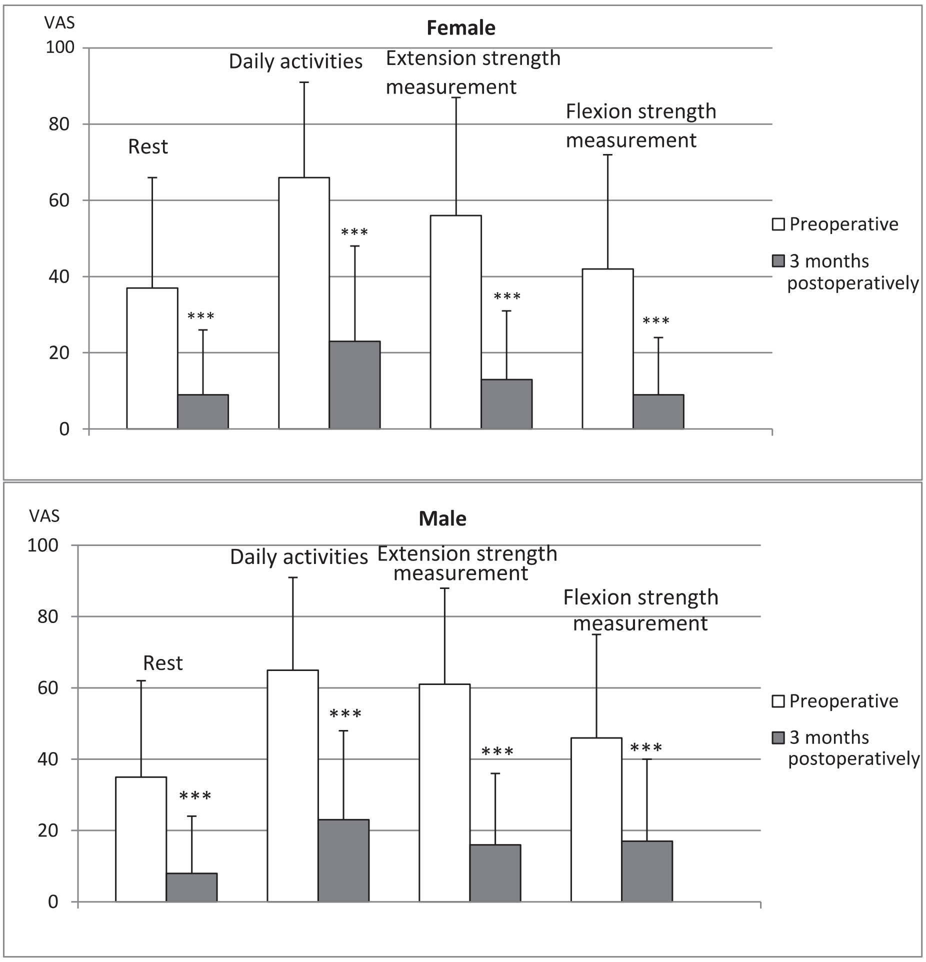


FIGURE 10 Intensity of low back pain in females (A) and males (B) (*** $p<0.001$).

Preoperatively, the ODI score was over 20 in 90% of patients, and the mean disability level was 45 (16) in females and 39 (17) in males. Three months postoperatively, the ODI values decreased to 23 (16) in females and 23 (14) in males ($p< 0.001$), but remained over 20 in 43% and over 40 in 15% of patients. The changes in the ODI were moderately associated with changes in trunk extension (r= -0.38, 95% CI: -0.50 to -0.23) and flexion (r= -0.43, 95% CI: -0.58 to -0.27) strength (Figure 11).

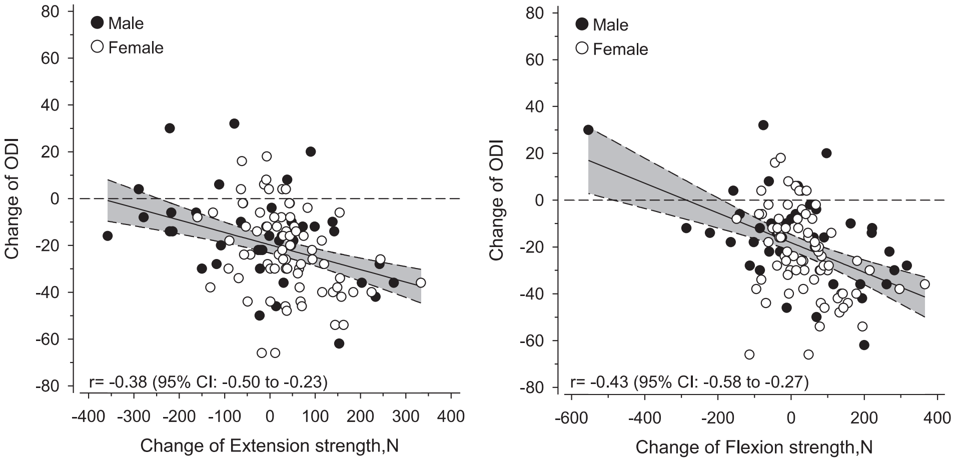


FIGURE 11 Association between change in trunk muscle strength and Oswestry Disability Index.

During the follow-up, TUG-test time decreased in females from 10,8 s to 8,4 s ($p<0.001$) and in males from 10,7 s to 7,9 s ($p<0.01$). The change in TUG test time was moderately associated with the changes in trunk extension (r=-0.37, 95% CI: -0.48 to –0.29) and flexion strength (r=-0.37, 95% CI: -0.52 to –0.25). There was also a moderate association between the change in the ODI and the change in TUG-test time (r= 0.35, 95% CI: 0.18 to 0.54).

5.2 Trunk muscle activity during isometric and dynamic exercises in healthy subjects (Study II, III)

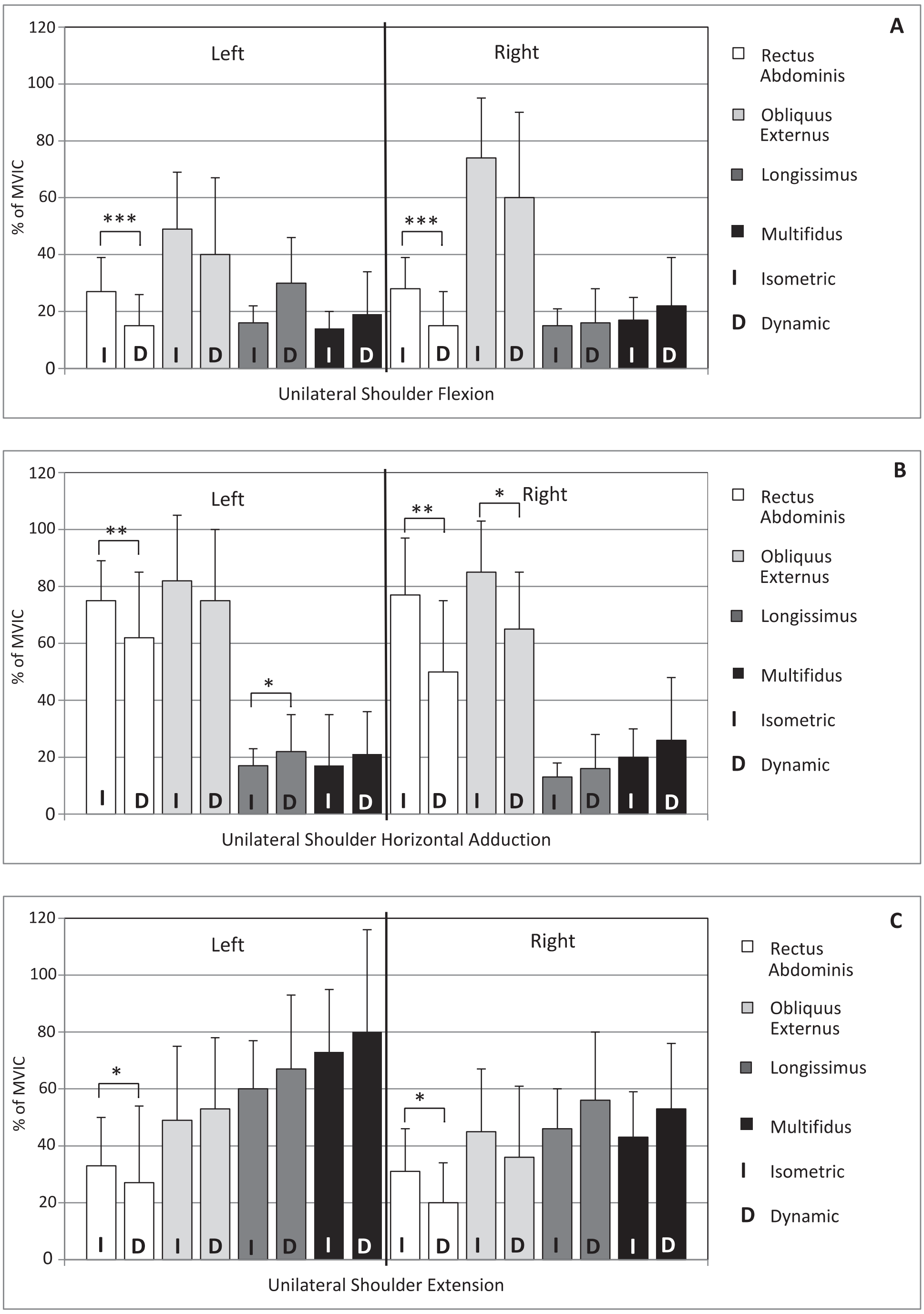
In healthy females, the values for maximal isometric trunk extension and flexion strength were 354 (98) N and 297 (71) N, and their trunk extension/flexion strength ratio was 1.23 (0.33). Of the upper limb NSC exercises, the highest maximal isometric strength was found during unilateral shoulder extension (234 (63) N) and the lowest during unilateral shoulder horizontal abduction (156 (51) N). The forces produced in unilateral shoulder extension and flexion were greater than those in unilateral shoulder horizontal abduction and adduction, or in bilateral shoulder extension ($p<0.001$) (Study II). In the dynamic upper limb exercises with pelvis fixation, the highest 1-RM resistance was achieved in unilateral shoulder extension exercise and the lowest load in unilateral shoulder flexion. The resistance was greater during the pulling (unilateral shoulder extension and horizontal adduction) compared to pushing (unilateral shoulder flexion and adduction) exercises ($p<0.001$). In the unilateral shoulder horizontal adduction and abduction exercises, the load was higher with pelvis fixation, compared to the same exercises without fixation ($p<0.001$) (Study III).

In studies II and III, the activation of the trunk muscles was, with some exceptions, at same level during both the isometric and dynamic upper limb exercises (Figure 12 A-E). The highest abdominal muscle activation was measured during bilateral shoulder extension and unilateral shoulder horizontal adduction.

In the isometric and dynamic 1 RM bilateral shoulder extension exercises, the mean activity level of the RA was 114% and 100%, respectively. The greatest activation of the OEA was measured during isometric bilateral shoulder extension exercise in which the left and right side activation of the OEA achieved 99% and 102 % of MVIC, respectively (Study II). The corresponding values during isometric horizontal adduction were 82% and 85 % of MVIC (Study II). The relative muscle activity during dynamic 1 RM shoulder horizontal adduction with pelvic fixation was 65% on the ipsilateral side and 75% on the contralateral side compared to trunk flexion (Study III).

The activity of the right and left longissimus during isometric trunk extension was significantly greater than the corresponding activation during the isometric ($p<0.001$) (Study II) and dynamic ($p<0.05$) 1 RM upper limb exercises (Study III). Of all the upper limb exercises, the greatest level of longissimus EMG amplitude was produced on the left side in unilateral shoulder horizontal abduction, in which it was 69% of MVIC during isometric and 67 % of MVIC during dynamic exercise.

In to the case of the isometric upper limb exercises, the LM muscles were activated to the greatest degree in unilateral shoulder horizontal abduction, in which the activation level of the LM on left side was 84% of MVIC. In the dynamic 1 RM exercises, the highest left side LM activation, 80% of MVIC, was achieved during unilateral shoulder extension. The LM amplitude levels during isometric unilateral shoulder extension and unilateral shoulder horizontal abduction were higher in left than right side ($p<0.01$) (Study II). Similarly, the dynamic unilateral shoulder extension exercise activated the left more than right side ($p<0.001$) (Study III).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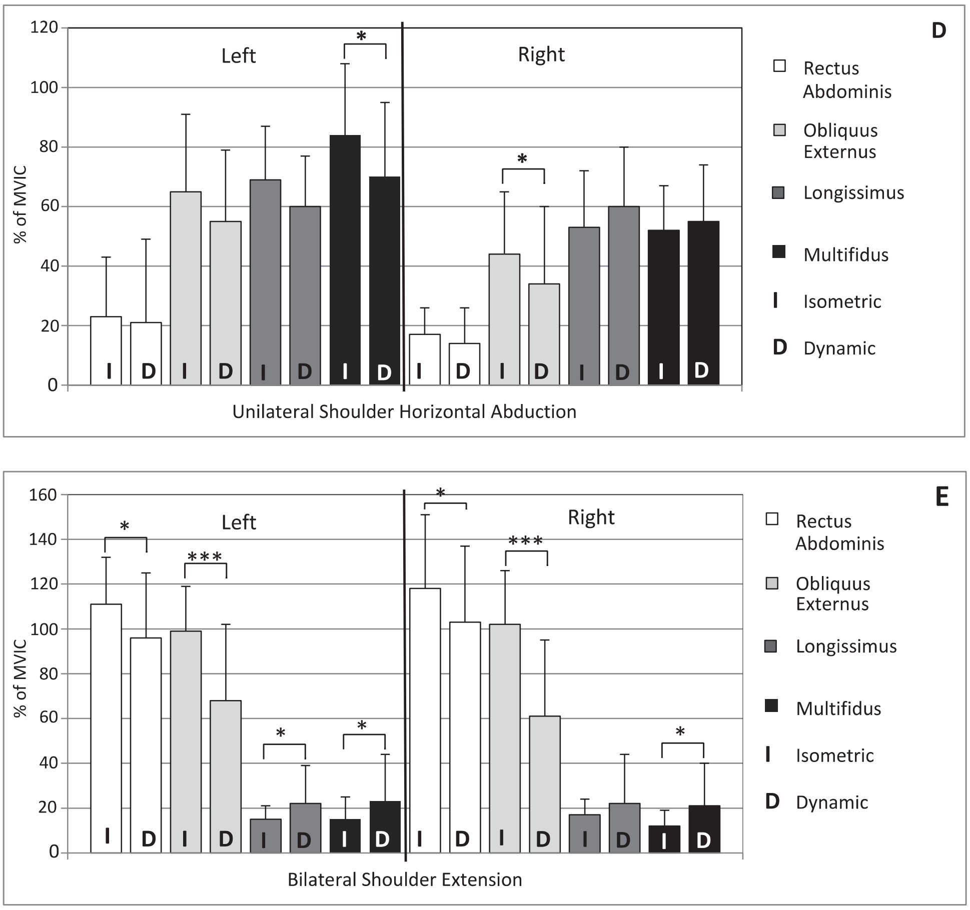

FIGURE 12 Muscle activity during maximal isometric and dynamic neutral spine control exercises (% of MVIC) (* p<0.05, **p<0.01, ***p<0.001).

Fixation of the pelvis affected both abdominal and back muscle activation (Study III). During dynamic unilateral shoulder horizontal adduction without pelvis fixation, the average activation of the RA and OEA was 64% and 44% lower than during the fixed exercise (p<0.001). The activity level of the abdominal muscles during unfixed exercise remained under 45% of MVIC. The activity levels of the longissimus and LM during unfixed shoulder horizontal abduction were 43% and 35% lower than the same exercise with fixation (p<0.001). During dynamic unilateral shoulder horizontal abduction without fixation, the activity levels of the longissimus and LM were under 50% of MVIC (Figure 13 A & B).

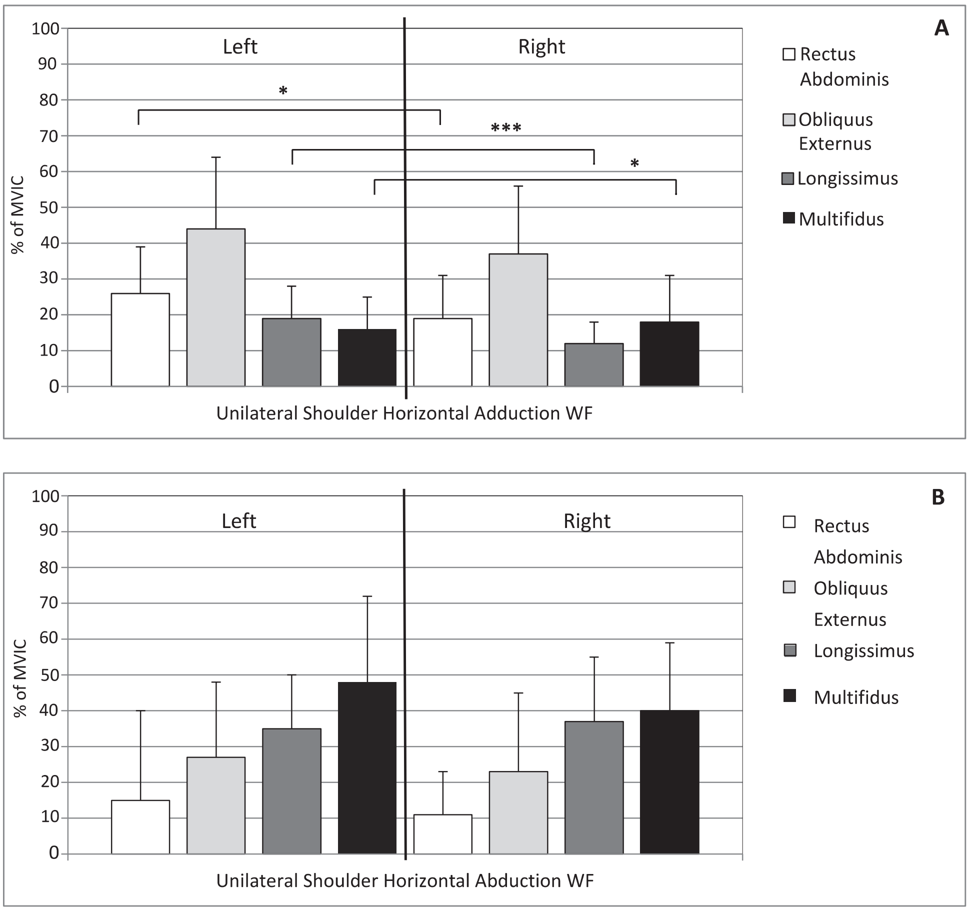

FIGURE 13 Muscle activity during maximal dynamic right shoulder horizontal abduction (A) and adduction (B) without pelvis fixation (WF) (% of MVIC) (* $p<0.05$, *** $p<0.001$).

5.3 Effect of neutral spine control exercises on the activation of trunk muscles in LSF patients (Study IV)

The mean (SD) maximal isometric trunk extension and flexion forces in patients after lumbar spine fusion were 342 (204) N and 404 (198) N, respectively. Extension/flexion strength ratio was 0.86 (0.33). Mean (SD) load in the pull machine varied from 6 (4) kg in bilateral shoulder flexion to 14 (9) kg in unilateral shoulder horizontal abduction.

The mean EMG activities of the abdominal muscles during the reference isometric trunk flexion exercises were generally higher than during the studied NSC exercises ($p<0.05$), with the exception of left side RA activity during the concentric phase of the bilateral shoulder extension exercise, in which the activity level of RA was 51 % of MVIC. The activity of the OEA was highest during unilateral shoulder horizontal adduction, 48% of MVIC, and unilateral hip extension exercises, 46% of MVIC (Figure 14 A & B).

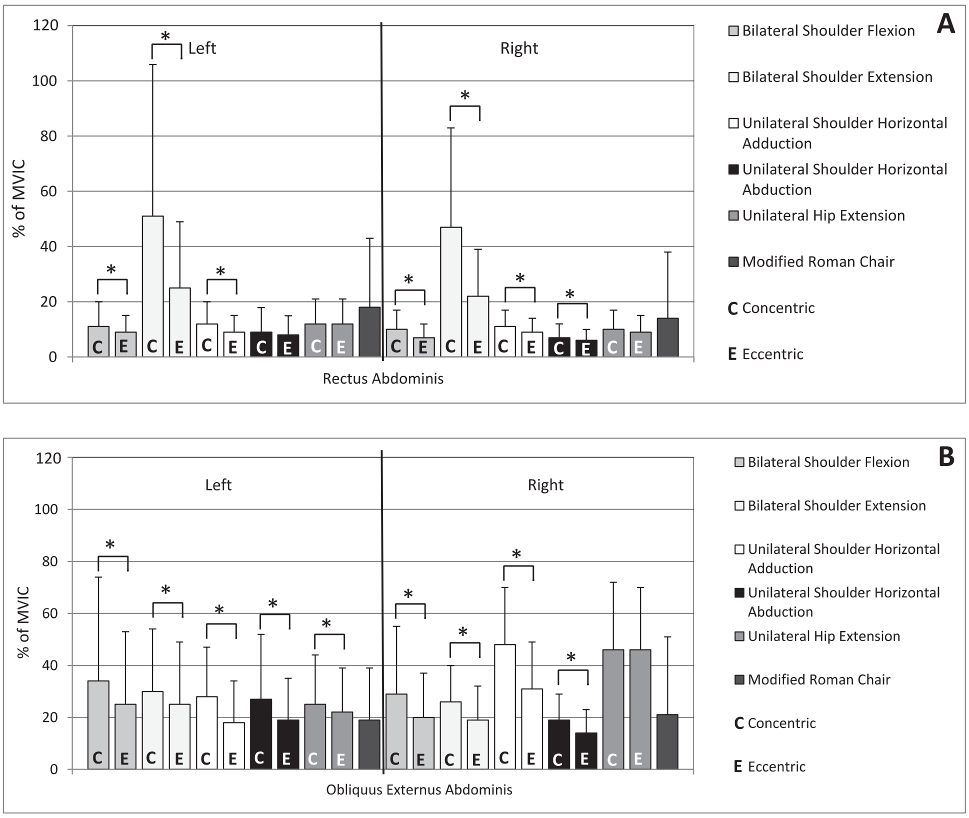

FIGURE 14 Activity of trunk flexors (A rectus abdominis, B obliquus externus abdominis) during neutral spine control exercises (% of MVIC) (* $p<0.05$).

The activity of the longissimus and LM during the reference isometric trunk extension was generally significantly higher than during NSC exercises ($p<0.05$), with the exception of the activity of the right side longissimus during the concentric and eccentric phases and the left side longissimus during the concentric phase of the bilateral shoulder flexion exercise and both side longissimus activity during the modified Roman chair. The activities of both longissimus and LM were highest during concentric phase of bilateral shoulder flexion and during the modified Roman chair exercises. The highest longissimus activity during these exercises was 78% and 83% of MVIC on the left side and 81% and 104% of MVIC on the right side. The corresponding values for LM were 60% and 64 % of MVIC on the left side and 65% and 62 % of MVIC on the right side (Figure 15 A & B).

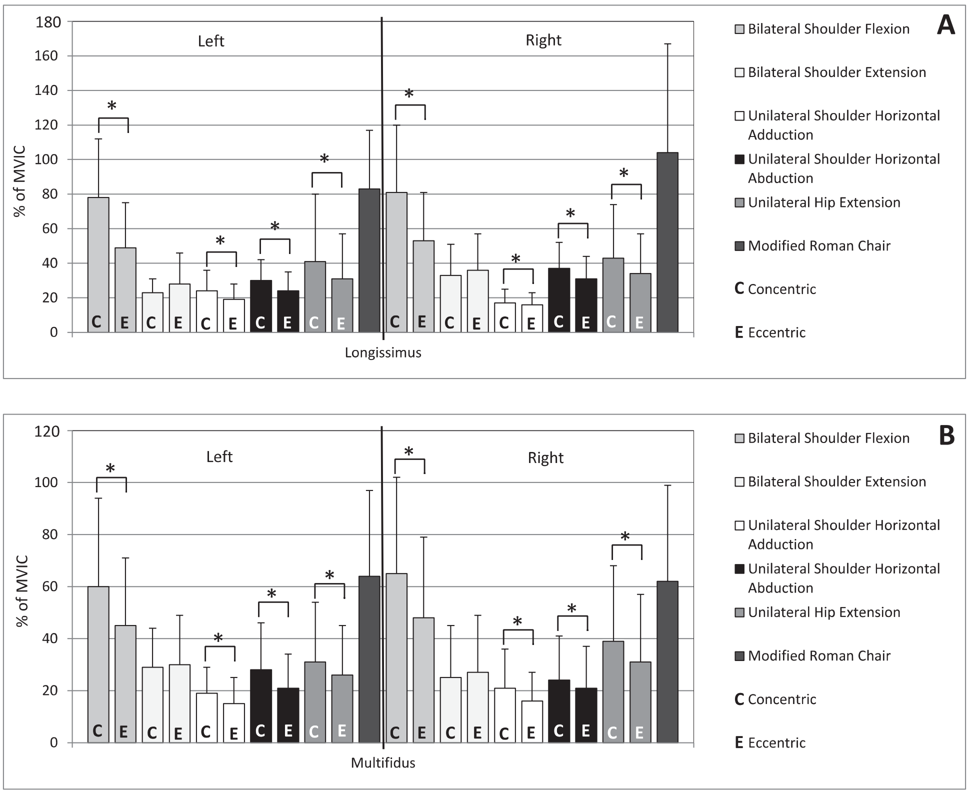

FIGURE 15 Activity of trunk extensors (A longissimus, B multifidus) during neutral spine control exercises (% of MVIC) (* $p<0.05$).

EMG activities in the dynamic exercises were higher during the concentric than eccentric phase of exercise ($p=0.036$), with a few exceptions (Figures 13 and 14).

Mean (SD) low back and lower extremity pain intensities during the previous week were 19 (19) and 15 (20), respectively. The corresponding values during isometric trunk extension were 12 (20) and 6 (18) and during isometric trunk flexion 6 (14) and 5 (16). Of the NSC exercises, the mean (SD) intensities of low back and lower extremity pain were the lowest, 3 (13) and 3 (7) respectively, during unilateral shoulder horizontal abduction and the highest, 16 (26) and 8 (19), during the modified Roman chair exercise. Pain intensity during any of exercises was not statistically higher than the average pain during the preceding week. Instead, low-back pain during unilateral shoulder horizontal abduction and unilateral hip extension was lower than the average pain during the previous week ($p < 0.05$).

6 DISCUSSION

Chronic pain, fear of painful movements, decreased physical activity due to pain, muscle injuries caused by the operation, and the fusion itself induce changes in back function in LSF patients. Change in muscle function may further slow recovery and cause postoperative disability. An effective postoperative exercise program should be based on knowledge of the extent of the surgery and the pain, disability, and performance capacity of the patient. The selection of exercises and intensity of training should be planned so that the objectives that have been set for the exercise program are achievable. In addition, to improve exercise adherence, patients need to be motivated and encouraged.

The process of developing an intervention program consists of several phases (Figure 16) (Campbell et al. 2000). In the present study, in Phase I, a literature review was performed to create the theoretical basis for the intervention and a prospective follow-up study was carried out to assess the pre- and post-operative clinical condition of LSF patients. This phase revealed what kinds of deficiencies LSF patients present in their back functions and how these should be take into account in the rehabilitation program. In Phase II, the feasibility of functional neutral spine control exercises was tested to find out how they should be performed i.e., how lever arms, pelvic stabilization and movement direction affect trunk muscle activity. In Phase III, testing of the proposed exercises was done in clinical setting with LSF patients to determine their feasibility of for rehabilitation purposes. In Phase IV, results of the preceding phases were combined with clinical knowledge to lay the foundation for the content of the intervention. The follow-up phase of the present RCT intervention study is currently in process, and effectiveness of the RCT will be reported elsewhere (Phase V).

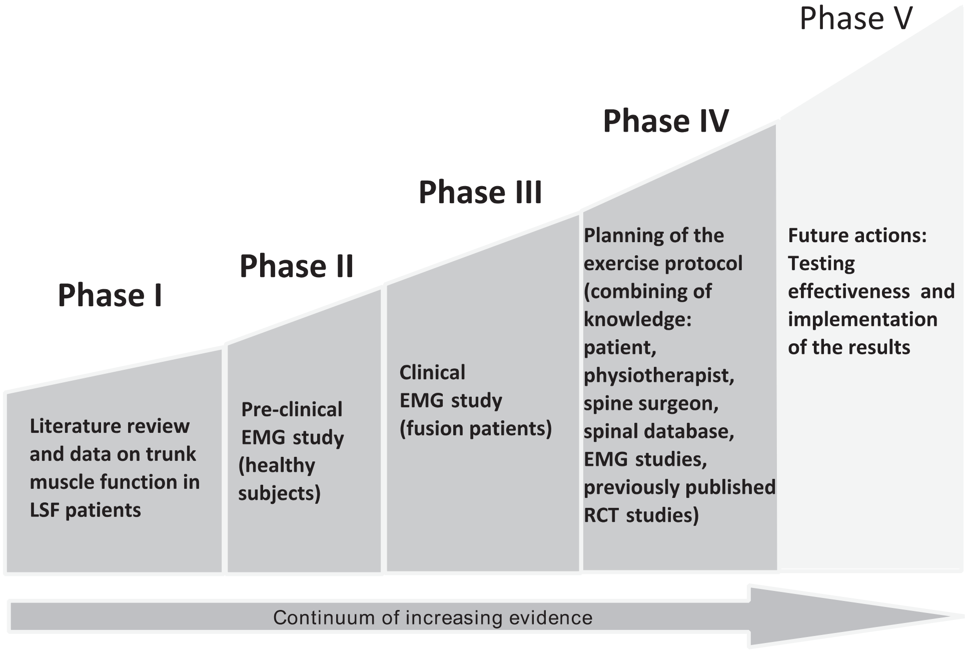

FIGURE 16 Phases in the design of the postoperative exercise intervention for LSF patients (Modified from Campbell et al. 2000).

6.1 Phase I: Trunk muscle function in LSF patients

The results of Study I indicated that lumbar spine fusion surgery in strict indications is effective in decreasing patient disability and pain. Pain during rest and daily activities decreased by more than 60% and disability improved (ODI) by more than 40% in both sexes during the first 3 months post surgery. Previous follow up studies have shown that the main effect of fusion on pain and disability is evident after the first 3 months and that thereafter improvements are minor (Abdu et al. 2009, Becker et al. 2010, Pekkanen et al. 2013b). Although the goals of the LSF operation were mainly achieved, ODI values were over 20 in 43% of patients and over 40 in 15% of patients.

The preoperative trunk muscle strength of these LSF patients, who had suffered back pain on average for 3 years, was poor. Although in females muscle strength increased statistically significantly during the follow-up, the strength of the trunk extensors and flexors was still only 29% and 36% of body weight. The preoperative strength of the trunk extensors and flexors were below the values of healthy control subjects (Biering-Sorensen 1984, Tiusanen et al. 1996, Paalanne et al. 2009). Interestingly, the increase in muscle strength after surgery was moderately associated with disability (ODI) improvement, supporting the use of strength training in the rehabilitation of LSF patients.

The results on the positive changes in strength level in females during the early recovery phase conflict with those of Keller et al. (2004), who reported a negative effect of fusion on trunk extension strength. Although in the present study muscle tissue injury due to the operation did not decrease the level of trunk extension strength, it may slow the recovery of muscle strength, as reported previously by Kim et al. (2005). Decreased trunk muscle performance in patients undergoing lumbar fusion may also be a result of longstanding pain and disability that have already caused alterations in the size, density, structure, and neural drive of the trunk muscles. Moreover age-related degeneration, leading for example, to changes in sagittal balance, and changes in the angles of the lumbar extensor muscle fibres may also have changed muscle function (Demoulin, Crielaard & Vanderthommen 2007, Singh, Bailey & Lee 2013).

Intensity of pain can partly explain the lower trunk muscle strength found in Study I. However, pain correlated only weakly with the trunk muscle strength values in the preoperative measurements. Further, although pain during testing decreased significantly at 3 months, the postoperative strength levels remained low. Thus, pain-related inhibition is not the only reason for the low strength values. In addition to structural changes in muscle tissue, the results may also be influenced by several individual confounding factors, such as motivation, pain tolerance, anticipation or fear of pain, thus rendering the patient incapable of producing a truly maximal effort (Mannion et al. 2001, Keller, Brox & Reikeras 2008). Therefore, level of muscle strength can be thought of as a functional strength level.

In addition to low preoperative strength levels and minor postoperative recovery, imbalance in force production between the trunk extensors and flexors was found in Study I. The preoperative extension/flexion strength ratio was less than 0.80 in both sexes and had decreased to 0.66 in males at the three-month postoperative follow-up, demonstrating that in these patients the trunk extensor muscles were weaker than the flexors. Previously, extension/flexion strength ratios below 1.0 have also been reported in CLBP patients, and postoperatively after lumbar disc, decompression, fusion surgery (Mayer et al. 1985, Häkkinen et al. 2003, Keller et al. 2003, Froholdt et al. 2011). The trunk extension/flexion strength ratio of LSF patients is clearly under the values of 1.15-1.34 reported in healthy population (Holmstrom, Moritz & Andersson 1992, Takemasa, Yamamoto & Tani 1995, Paalanne et al. 2009).

From preoperative to three months postoperatively, functional mobility measured by TUG-test time improved significantly (2,4 s and 2,8 s). The postoperative TUG-test times of the LSF patients were on the same level as the reference values of healthy people (Isles et al. 2004, Bohannon 2006). A similar improvement of 2 seconds in the TUG-test results between the measurements before and 3 months after LSF, found in our study, have previously been reported by Nielsen et al. (2010). The TUG test measures patient ability to stand up, sit down, walk and turn during walking, and therefore sufficient muscle strength, coordination and dynamic balance are needed during the performance of the test. The improvement in the TUG test results is interesting in light of evidence that postural control is not automatically improved, even if lumbar proprioception and feed-forward control of the paraspinal muscles are recovered after lumbar surgery (Leinonen et al. 2003). The changes in TUG-values may also be related to improvement of motor function in the lower extremities due to decompression of the spinal nerves.

The results of the follow-up study indicate that while LSF was effective in decreasing pain and disability (ODI), the postoperative disability level continued to be moderate or severe in 43 % of patients. Low trunk muscle strength and trunk extensor/flexor imbalance indicate a need for strength training, which should focus, in particular, on the trunk extensor muscles. The use of progressive intensive trunk muscle strength training in the rehabilitation of LSF patients is also supported by the negative association between the postoperative changes in muscle strength and disability and the positive association between muscle strength and functional mobility (TUG-test). Furthermore, evaluation of patients' deficiencies in back function is important for planning the exercise program, for documenting its efficacy and for providing information about performance and progression that can help to improve exercise adherence and increase physical activity. Moreover, patients who have functional deficiencies and need special attention during rehabilitation can be identified in this postoperative stage.

6.2 Phase II: Trunk muscle activation during isometric and dynamic upper extremity exercises in healthy subjects

The purpose of the preclinical EMG studies was to determine if upper extremity exercises performed with the lumbar spine in the neutral position and with maximal isometric or dynamic 1-RM resistance are able to load the trunk muscles sufficiently to improve muscle strength characteristics. The progressive resistance training recommendations of American College of Sports Medicine are considered as a reference for training intensity. An activity level of 40-60% of 1 RM is thought to be sufficient to achieve improvement in muscle endurance and a level of 60-70% of 1 RM to improve muscle strength (American College of Sports Medicine 2009). Thus, EMG activity of at least 60% of MVC is required to achieve a strength gain, neural adaptations, and muscle fibre hypertrophy (Andersen et al. 2006). The selection of movement-based exercises for studies was based on preventing the isolation of specific trunk muscles and instead developing the capacity of the trunk muscles to control the neutral spine position in functional movements.

In healthy subjects, an adequate abdominal strength training level was achieved during isometric and dynamic unilateral shoulder horizontal adduction and bilateral shoulder extension. In addition, the OEA activity level exceeded 60 % of MVIC during unilateral shoulder flexion. Previously, over 60% of MVC RA activity during upper extremity exercises during bilateral shoulder extension (Arokoski et al. 2001) and over 60% of MVC OEA and OIA activity during unilateral shoulder horizontal adduction have been reported (Santana, Vera-Garcia & McGill 2007). However, in the present study pelvic fixation was needed for higher activity level. During unilateral shoulder horizontal adduction without fixation, both RA and OES activities were 64 % and 44 % lower than during the same exercise with fixation.

Both isometric and dynamic unilateral shoulder extension and horizontal abduction exercises induced activity level over 60% of MVIC in the longissimus and LM muscles. In previous studies, similar erector spinae and/or LM activity levels have been achieved during trunk extension, bilateral hip extension, and Roman chair exercises (Arokoski et al. 1999, Arokoski et al. 2001, Ekstrom, Osborn & Hauer 2008, Colado et al. 2011), during exercise with extensor training devices (Stevens et al. 2008) and during squats, deadlifts, and lunges with a barbell (Nuzzo et al. 2008, Colado et al. 2011). However, trunk extensor activity higher than the strength training level during upper limb exercise has only been reported in one study, that by Arokoski et al. (2001). They measured over 70% of MVIC activity in the thoracal part of the erector spinae during bilateral shoulder extension exercise. The activity of the LM was 50% of MVIC during the same exercise (Arokoski et al. 2001).

Fixation of the pelvis is needed to achieve higher trunk muscle activity when upper limb exercises are performed in the standing position. When unilateral shoulder horizontal abduction exercise was performed without pelvic fixation, the activity level of the longissimus and LM were 43% and 35% lower, respectively, than during corresponding exercise with fixation.

The results of the cross-sectional EMG studies showed that during the integrated core and shoulder exercises with maximal resistance and pelvic fixation it was possible to achieve a trunk muscle activity level which can be considered sufficient to improve both muscle strength and endurance. In these exercises, the trunk muscles are trained in their functional roles of controlling lumbopelvic stability and creating proximal stability during limb movements. The neutral position of the lumbar was maintained during all exercises, which may improve the capacity of the spinal structures to withstand the loads directed on it (McGill 2001). While the use of pelvic fixation in the exercises performed in the standing position increased trunk muscle activity during the upper limb exercises, it should be noted that sufficient fixation of the pelvis is challenging to achieve e.g. in home-based training.

6.3 Phase III: Trunk muscle activation during neutral spine control exercises in LSF patients

In Phase III, the results of studies II and III were applied to LSF patients. The neutral spine control exercises studied here were performed with a 10 RM resistance as 1 RM training is not appropriate in clinical settings, especially in postoperative patients. In addition, hip extension and Roman chair exercises, which are widely used in low back pain rehabilitation, were included in the study. Because fixation of pelvis cannot be used in home-based exercise, it was also tested whether sitting posture would stabilize the pelvis sufficiently to allow higher loading on the trunk muscles.

The activity levels of the RA and OEA muscles remained below 60% of MVIC during all the studied exercises in the LSF patients. However, during bilateral shoulder extension, unilateral shoulder adduction and hip extension, RA and OEA activity reached 50% of MVIC. Thus, these exercises are useful for muscle endurance training after LSF. The bilateral shoulder flexion and Roman chair exercises activated both the longissimus and LM to a level that may be sufficient for muscle strength training.

It has been speculated that exercises which are able to cause high activity of the lumbar part of the erector spinae and LM provide insufficient stimulus to induce strength adaptation. This may be due to simultaneous derecruitment of the lumbar muscles and increased recruitment of the thoracic erector spinae and hip extensors during fatiguing exercises (Steele, Bruce-Low & Smith 2013). An increase in hip extensor activity during performance may be avoided by loading of the lumbar muscles via the upper extremities, such as in bilateral shoulder exercise.

Activity of the latissimus dorsi and gluteal muscles was not measured in the present study, but previous EMG studies indicate that rowing exercises in the standing position are able to activate those muscles simultaneously with trunk extensor muscles (Fenwick, Brown & McGill 2009), and thus rowing exercises may also affect the structure of the thoracolumbar fascia. The posterior layer of the TLF plays an integrating role in load transfer between the arms, spine, pelvis, and legs, and the stability of the lumbar spine (Carvalhais et al. 2013). Because the latissimus dorsi, TLF, and gluteus maximus also cross the sacroiliac joint, the tensioning of fascia due to activation of these muscles also stabilize the sacroiliac joint (Hukins, Aspden & Hickey 1990, Adams & Dolan 2007, Barker & Briggs 2007, Willard et al. 2012). The study of Jeong et al. suggested that sagging of the thoracolumbar fascia may predispose patients to the development of adjacent segment disease following LSF (Jeong et al. 2013). Exercises which activate muscles attached to the TLF may have positive effect on lumbar spine function in LSF patients.

The average intensities of low back and lower extremity pain during all the studied exercises, including reference exercises, remained lower than the average pain experienced during daily activities the previous week. The results of Study IV demonstrate that neutral spine exercises activate the trunk muscles effectively without increasing pain and are therefore feasible for improving muscle endurance and strength in LSF patients after surgery. This was the first EMG study to report on the level of pain in LSF patients during the specific exercises. Some previous studies have measured trunk muscle activity during trunk muscle exercises in patients with chronic low back pain (Danneels et al.

2002, Hubley-Kozey & Vezina 2002, Arokoski et al. 2004, Marshall, Desai & Robbins 2011), but did not report on pain intensity during exertion.

6.4 Phase IV: Planning of postoperative exercise program

The main goals of lumbar fusion surgery and postoperative rehabilitation are relief of pain and disability and restoration of back function. The aim of a proper exercise program is (i) to improve the level of strength of the trunk muscles, (ii) correct the trunk muscle extension/flexion strength ratio, (iii) increase the capacity to control the neutral spine position, and (iv) decrease adverse tissue strain at the adjacent segment level. Because of disc degeneration, elderly subjects often have a positive sagittal balance (anterior deviation of the C7 plumb line) and fusions may present an even greater challenge for maintenance of compensatory local hyperlordosis. In these patients, good condition of the extensor muscles is important to maintain sagittal balance (Benoist 2003, Barrey et al. 2011).

The post-operative exercise protocol was designed on the basis of a literature review, spinal database, and pre-clinical and clinical EMG studies. The data collected were combined with clinical knowledge obtained from a multidisciplinary group in the study hospitals and feedback from patients (Figure 16).

Study V describes the rationale and design of a study for assessing the effectiveness of long-term combined back-specific (combination of resistance training and training of control of the neutral lumbar spine position) and aerobic training in post-operative rehabilitation after lumbar spine fusion. Trunk muscle function and health-related fitness in patients with chronic low back pain are often so extensively impaired that it is important to evaluate the effectiveness of comprehensive post-operative training. The effectiveness of exercise interventions are partly adherence-dependent, and thus special attention is paid to patients' goal setting, monitoring of progression and motivation.

The intervention comprises three different areas: (i) back specific exercises, (ii), aerobic exercise/increasing physical activity, and (iii) improving exercise adherence (Figure 17).

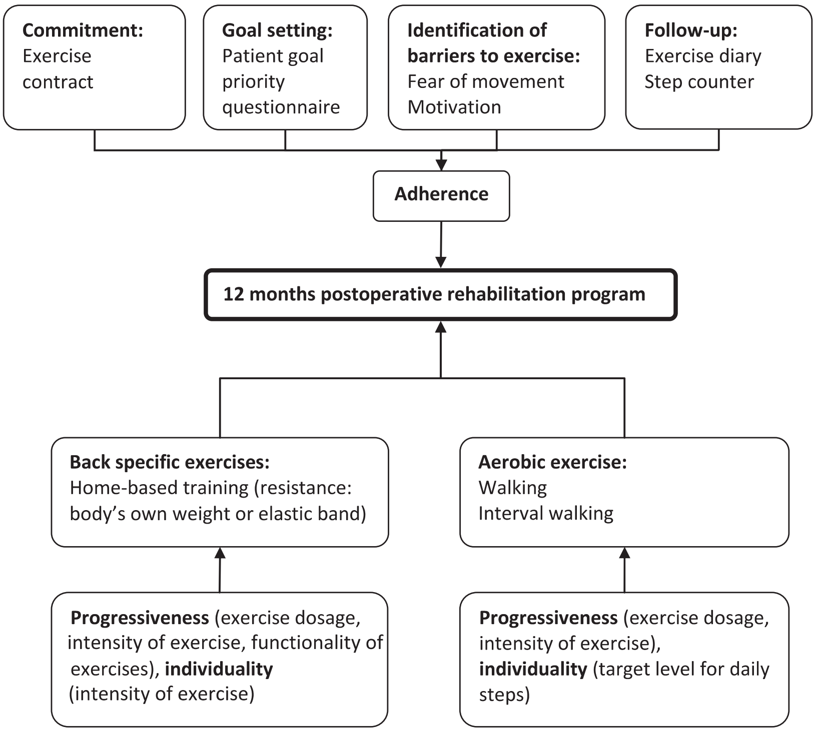

FIGURE 17 Content of the intervention.

In the back-specific exercises, the functionality and intensity of exercise is increased progressively and individually during the intervention. The number of repetitions are varied between 10 (muscle strength and lumbar spine position control exercises) and 20 (muscle endurance) (Appendix 1a&b). Control of the neutral lumbar spine position is dependent on the precision of the function of the central nervous system and capacity of the trunk muscles to generate force (McGill et al. 2003, Reeves, Narendra & Cholewicki 2007). Thus, through a proper trunk muscle coactivation strategy, the exercises should improve body position awareness and trunk muscle performance capacity (Hodges & Cholewicki 2007, Reeves, Narendra & Cholewicki 2007, Stokes, Gardner-Morse & Henry 2011). Neutral spine control exercises performed via the upper extremities integrate movement patterns that simultaneously activate both the abdominal and the lumbar muscles. Coactivation of the trunk extensor and flexor muscles increases stiffness on the lumbar spine, which is important during high loading tasks, such as lifting (van Dieen, Kingma & van der Bug 2003, Vera-Garcia et al. 2006). Maintaining the neutral spine position during exercises may also improve exercise safety. Dynamic exercises which allow the lumbar spine to flex would changes the line of action of the lumbar parts of the erector spinae and compromise their role to support anterior shear forces (McGill, Hughson & Parks 2000).

According to the meta-analysis of Line et al. (2011), CLBP patients with high levels of disability are likely have low levels of physical activity. In addition CLBP patients have reduced aerobic capacity compared to healthy asymptomatic subjects (Duque, Parra & Duvallet 2011). Thus, the aerobic exercise program is aimed at increasing the level of physical activity and improving patients' aerobic capacity. In addition, regular physical activity has a number of favourable metabolic, hormonal, neurological, respiratory, and mental effects (Karpansalo et al. 2003). In a walking exercise program, the number of daily steps is gradually increased according to the baseline level (Appendix 2) (Tudor-Locke & Bassett 2004, Tudor-Locke et al. 2008, Tudor-Locke, Washington & Hart 2009).

In the guidance session, patients make a personal exercise contract and set their personal goals (Åsenlöf, Denison & Lindberg 2004). To improve exercise adherence, attempts are made to identify barriers to exercise, such as kinesiophobia (Rhodes & Fiala 2009, Jordan et al. 2010). The patient's experiences of the previous training phases are reviewed and their progression in the back-specific and aerobic exercises checked with the physiotherapist during each guidance sessions.

6.5 Phase V: Testing of the protocol

The final phase in the process of developing an intervention is the testing of its effectiveness and implementation of the results. In the present instance, effectiveness will be tested in a RCT study comparing the intervention with the usual postoperative rehabilitation. The selection of patients for the RCT study aims to reflect the patient population that usually undergoes this particular operation, and hence strict exclusion criteria concerning age or comorbidities will not be used. This will improve the generalizability and implementability of the results. The results will have practical value in the planning and development of the programs for postoperative rehabilitation in the case of LSF patients.

6.6 Methodological considerations

There are a number of factors that have to be taken into account when interpreting the results of Study I-IV. The same isometric trunk muscle strength testing method was used in all studies. The method was selected on the basis of factors concerning reliability and safety. Isometric measurements were used as the use of dynamic trunk muscle measurements could increase the risk of breaking the fusion device/instrumentation or causing the pulling out of screws in the early postoperative phase.

Posture during trunk muscle strength tests also affect the maximal activity attained. It was assumed that each studied muscle group maximal activity would be achieved during maximal isometric extension or flexion. However, maximal level of activity of the abdominal muscles during isometric trunk flexion and of the back muscles during trunk extension were exceeded during several exercises in studies II, III, and IV. Individual responses to each MVC exercise vary markedly, and while not all subjects are able to perform at maximum EMG activity in the reference exercise, they may show maximum EMG activity in other exercises. This phenomenon inevitably affects the results, but it cannot be wholly avoided. Trunk muscles activity levels above 100% of MVC have also been reported in several other EMG studies (Arokoski et al. 2001, Santana, Vera-Garcia & McGill 2007, Fenwick, Brown & McGill 2009, Marshall, Desai & Robbins 2011). Although the testing position has some effect on the attainment of maximal activity, the use of the same trunk position during MVIC measurements and during the exercises studied in this research are likely to improve the validity of the EMG measurements.

Wide individual variation was observed in the normalized EMG values. Muscles are not activated to the same relative level by all exercises in all subjects. Thus, the relative activity levels reported for the different exercise efforts can only act as a guide in the planning of exercise programs. The normalization of activity to maximal voluntary contraction is challenging in pain patients, whose willingness to produce maximal effort may be limited (Marras & Davis 2001). The possibility that pain or fear of pain had some effect on the results in the LSF patients in Study IV cannot be completely excluded, although pain intensity remained at relatively low levels during all measurements.

With surface EMG electrodes, it is only possible to measure the activity of the superficial muscles. However, possible cross-talk from deeper muscles needs to be taken into account in the interpretation of EMG data. The OIA and possibly, to some degree also, the TrA affect the level of activity of the flat OEA muscles, as they are located underneath that (Ng, Kippers & Richardson 1998). The effect of cross-talk on OEA activity is probable the greatest in exercises which result in loads being directed at the trunk in a horizontal rotational direction (Urquhart & Hodges 2005), such as in unilateral shoulder horizontal adduction. It is also unclear whether it is actually possible to study the activity of the LM through surface electrodes (Arokoski et al. 1999, Stokes, Henry & Single 2003). Stokes et al. (2003) reported that intramuscular electrodes are required to measure multifidus activity, while according to Arokoski et al. (1999), surface EMG measurements can be used in the assessment of multifidus muscle function.

The degree of EMG activation is only an indication of exercise intensity. The fact that the EMG studies demonstrated high trunk muscle activity during several upper extremity exercises should not be regarded direct evidence that by performing these exercise it is possible to improve muscle strength levels (Steele, Bruce-Low & Smith 2013). Thus, an RCT study that includes neutral spine control exercises is needed to demonstrate the effect of these exercises on trunk muscle strength.

7 MAIN FINDINGS AND CONCLUSIONS

The main findings in the present study can be summarized as follows:

1. Patients undergoing lumbar spine fusion had low trunk extensor and flexor strength. In addition, the force production of the trunk extensor and flexor muscles was imbalanced.
2. After lumbar spine fusion and early three months recovery, disability lessened and pain decreased significantly, whereas the changes in trunk muscle function were minor indicating that spontaneous physical activity and light trunk muscle exercises do not increase enough trunk muscle strength.
3. Surface electromyographic measurements showed that neutral spine control exercises, performed in the standing position, elicit sufficient activity of the trunk muscles to improve their endurance and strength characteristics. However, the use of pelvic fixation is needed to increase the level of activity of the abdominal and back muscles.
4. The high level of trunk muscle activity and low intensity of pain observed during the exercises support the use of neutral spine control exercises for improving muscle strength in LSF patients.

In conclusion, the result of the present study suggests that intensive training is needed to improve trunk muscle strength levels and correct trunk extensor and flexor strength imbalance after lumbar spine fusion. Training which includes dynamic upper limb pushing and pulling exercises is feasible for this purpose in postoperative rehabilitation. The findings of the present research were utilized in planning of a postoperative rehabilitation intervention. The effectiveness of the developed back-specific and aerobic exercise program in comparison to usual postoperative rehabilitation will later be evaluated in an RCT study. The future study will be the first study to evaluate the progressive, long-term, home-based intervention in rehabilitation after lumbar spine fusion. The results will have practical value in the planning and implementation of treatment options after lumbar spine fusion. The follow-up phase of the RCT study is currently in process and thus results are not included in this thesis.

YHTEENVETO (FINNISH SUMMARY)

Alaselkäkivut ovat yleinen ongelma. Kroonisen alaselkäkivun hoito on yleensä konservatiivista, mutta jos sillä ei saavuteta riittävää apua ja oireet ovat vaikeat, voidaan tiettyjen selkärangan muutosten kuten nikamanliukuman hoidossa päätyä lannerangan jäykistysleikkaukseen. Lannerangan jäykistysleikkaus on vaativa leikkaus, johon liittyy myös lannerangan ojentajalihasten surkastumista. Huolellisesti suunnitellulla ja toteutetulla leikkauksen jälkeisellä harjoittelulla on mahdollista vaikuttaa lihasten rakenteessa ja toiminnassa tapahtuneisiin muutoksiin ja sitä kautta vaikuttaa potilaan kokemaan kipuun ja toimintakykyyn. Rakenteellisten ja toiminnallisten muutosten aikaansaamiseksi harjoittelun tulee olla riittävän intensiivistä. Jäykistysleikkaukseen jälkeisessä harjoittelussa on hyvä käyttää harjoitteita, joissa lanneranka säilyy suorituksen aikana keskiasennossa. Näin vähennetään jäykistettyyn ja jäykistyksen viereiseen alueeseen kohdistuvaa kuormitusta.

Tämän väitöskirjatutkimuksen tarkoituksena oli selvittää henkilöiden, joille oli tehty selkärangan jäykistysleikkaus, vartalolihasten voimatasoa, alaselkäkivun intensiteettiä, sekä toiminta- ja liikkumiskykyä. Tämän tiedon perusteella kehitettiin harjoitteluohjelma jäykistysleikkauksen jälkeiseen kuntoutukseen.

Tutkimuksen ensimmäisen vaiheen mittaukset suoritettiin ennen leikkausta sekä kolme kuukautta leikkauksen jälkeen. Tutkimuksen tähän vaiheeseen osallistui yhteensä 114 potilasta, joille suoritettiin lannerangan jäykistysleikkaus Tampereen yliopistollisessa sairaalassa tai Keski-Suomen keskussairaalassa. Tutkimuksen toisessa vaiheessa tutkittiin erilaisten yläraajoilla suoritettujen veto- ja työntöliikkeiden vaikutusta vartalolihasten aktiivisuuteen elektromyografia-mittauksilla. Lisäksi testattiin harjoitteiden aikaisen lantion tuennan vaikutusta lihasten aktiivisuustasoon. Mittauksiin osallistui sekä terveitä henkilöitä (n=20) että lannerangan jäykistysleikattuja potilaita (n=22).

Tulokset osoittivat, että lannerangan jäykistysleikkaukseen menevillä henkilöillä vartalon lihasvoimataso on hyvin alhainen ja erityisesti voimatason aleneminen on havaittavissa vartalon ojentajalihaksissa. Vaikka lannerangan jäykistysleikkaus vähensi alaselkäkivun intensiteettiä yli 65%:a ja paransi toimintakykyindeksiä 47%:a kolme kuukautta leikkauksen jälkeen, vartalolihasten voimatasossa tapahtuneet muutokset olivat vähäisiä ja voimataso pysyi yhä matalalla. Seurannan aikana tapahtuneet lihasvoimamuutokset olivat yhteydessä toimintakyvyssä tapahtuneisiin muutoksiin.

Vartalolihasten aktiivisuusmittauksen perusteella yläraajoilla suoritettujen työntö- ja vetoharjoitteiden aikana on mahdollista sekä vatsa- että selkälihasten osalta saavuttaa kuormitustaso, jolla lihasvoimaa voidaan parantaa. Korkeamman lihasaktiivisuuden saavuttaminen edellytti liikesuoritusten aikaista lantion tukemista. Myös selkäleikatut potilaat saavuttivat kotiharjoitteluun sovellettavissa olevilla yläraajaharjoitteilla kuormitustason, jolla vartalon ojentajien lihasvoimaa voidaan harjoittaa. Yläraajaharjoitteiden aikainen kivun intensiteetti oli vähäinen, joten tältäkin osin tutkitut harjoitteet soveltuva leikkauksen jälkeiseen kuntoutukseen.

Leikkauksen jälkeinen normaalin kuntoutuskäytännön mukainen kevyt harjoittelu sekä asteittainen paluu päivittäisiin aktiviteetteihin ei ollut riittävää parantamaan potilaiden vartalolihasten voimaa. Siten vartalolihasten ja erityisesti selän ojentajalihasten voimatason parantamiseksi tarvitaan progressiivista ja riittävän intensiivistä harjoittelua. Vartalolihasten lihasvoimaharjoitteluun voidaan käyttää lanneranka keskiasennossa suoritettuja yläraajoilla tehtäviä veto- ja työntöharjoitteita.

Tutkimuksen viimeisessä vaiheessa tutkimustuloksia, sekä tutkimussairaaloissa selkäleikattujen hoitoon ja kuntoutukseen osallistuneen moniammatillisen tiimin kliinistä kokemusta hyödyntäen, suunniteltiin selkäspesifiä ja aerobista harjoittelua yhdistelevä kuntoutusohjelma. Suunnitellun kuntoutusohjelman vaikuttavuutta testataan satunnaistetussa kontrolloidussa tutkimuksessa. Tuleva tutkimus on ensimmäinen tutkimus, jossa arvioidaan progressiivisen pitkäkestoiseen kotiharjoitteluun perustuvan harjoitteluohjelman vaikuttavuutta lannerangan jäykistysleikkauksen jälkeisessä kuntoutuksessa. Vaikuttavuustutkimuksen seurantajakso on vielä menossa ja tulokset eivät siten sisälly tähän väitöskirjatutkimukseen.

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Appendix 1a

Back-specific exercise program

Phase	Back specific exercises	Goal of the exercise
I	1. Squat (SP, EB) 2. Abdominal crunch (SUP) 3. Hip abduction (CLP) 4. Hip abduction and external rotation (SLP, EB) 5. Hip extension (PRO) 6. Hip extension (FPKP, EB) Sets x Repetitions: 2 x 10-15-20	MS ME CNSP CNSP/ME CNSP CNSP/ME
II	1. Squat (SP, EB) 2. &3. Bilateral shoulder extension and flexion (SP, EB) 4. Heel slide or leg lift and knee extension with one leg (SUP) 5. Hip extension or hip extension and knee extension (CLP) 6. Hip abduction (SLP, EB) 7. Hip extension (EB) or bird dog exercise (FPKP) Sets x Repetitions: 2 x 10-15-20	MS ME/MS CNSP CNSP/ME CNSP/ME CNSP/ME
III	1. Squat (SP, EB) 2. & 3. Bilateral shoulder extension and flexion (SP, EB) 4. Leg lift and knee extension with one leg (SUP) 5. Hip extension and knee extension (CLP) 6. Bird dog exercise (FPKP) 7. Hip abduction (SP) Sets x Repetitions: 2-3 x 10-15-20	MS ME/MS CNSP CNSP/ME CNSP/ME CNSP/ME
IV	1. Squat (EB) or forward lunge (SP) 2. Waiters bow exercise with elastic band (SP, EB) 3. & 4. Bilateral shoulder extension and flexion (SP, EB) 5. & 6. Unilateral shoulder horizontal adduction and abduction (SIP, EB) 7. Hip abduction (SP, EB) Sets x Repetitions: 2-3 x 10-15-20	MS MS ME/MS CNSP/ME CNSP/ME
V	1. Forward lunge (SP) 2. Waiters bow exercise (SP, EB) 3. & 4. Unilateral shoulder horizontal adduction and abduction (SP, EB) 5.& 6 Downward chop and upward chop (SIP, EB) 7. Hip abduction (SP, EB) Sets x Repetitions: 2-3-4 x 10-15-20	ME/MS MS CNSP/ME CNSP/ME CNSP/ME
VI	1. Forward lunge (SP) 2. Waiters bow exercise (SP, EB) 3. & 4. Unilateral shoulder horizontal adduction and abduction (SP, EB) 5. & 6. Downward chop and upward chop (SP, EB) Sets x Repetitions: 2-3-4 x 10-15-20	ME/MS MS CNSP/ME CNSP/ME

SP, standing position; SUP, supine position; CLP, crook lying position; SLP, side lying position; PRO, prone position; FPKP, four-point kneeling position; SIP, sitting position; EB, with elastic band resistance; MS, muscle strength; ME, muscle endurance; CNSP, control of the neutral lumbar spine position.

Appendix 1b

Phase I


1


2

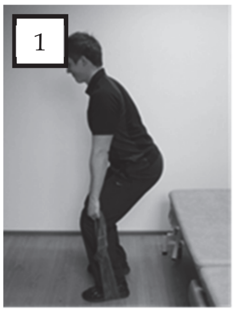

3

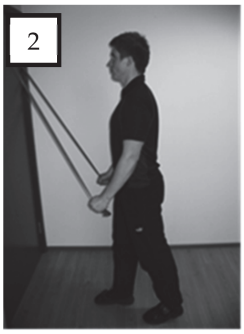

4

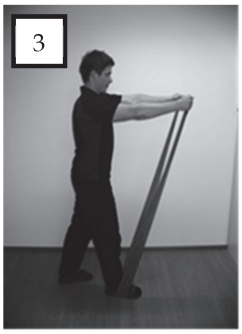

5

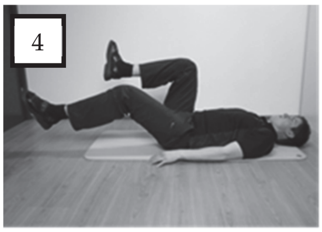

6

Phase II









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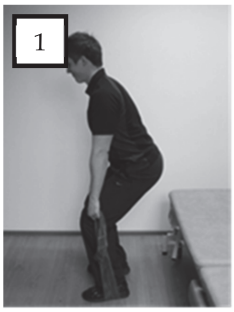
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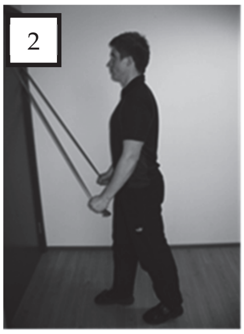
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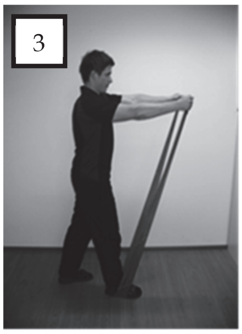
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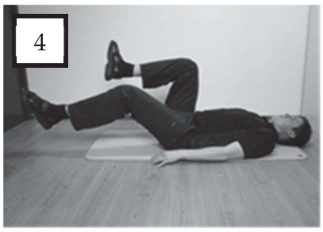
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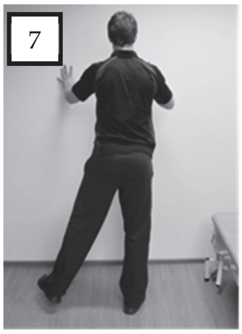
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Phase IV

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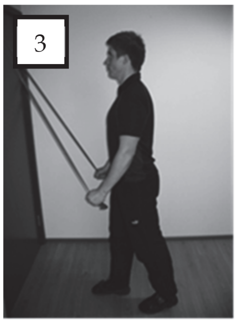

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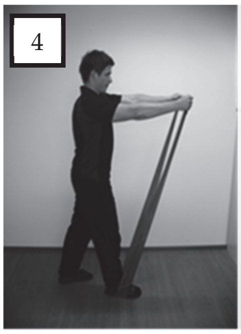

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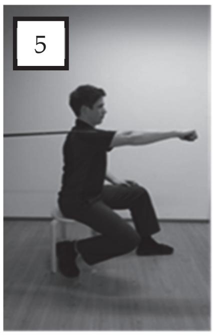

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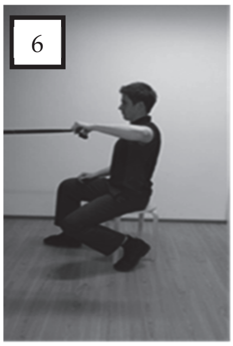

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Phase V


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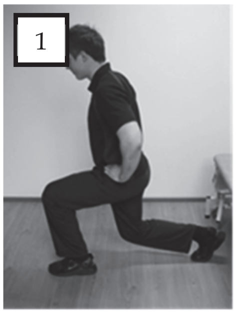
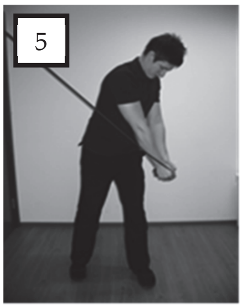
Phase VI





Appendix 2

The number of daily steps

Aim	Model of progression
10 000 steps/day, if: age under 65 years, healthy and no restrictions to increase physical activity	1. If baseline level <5 000 (sedentary), number of steps is increased 15% every other months until the target level is reached 2. If baseline level 5 000 - 7 499 (”low active”), number of steps is increased 10% every other months until the target level is reached 3. If baseline level 7 500 - 9 999 (”somewhat active”), number of steps is increased 5% every other months until the target level is reached 4. If baseline level >10 000 (active), this level is maintained or number of steps is increased 5% every other months until 12 500/day (”highly active”) is reached (Categorized according to (Tudor-Locke et al. 2008)
7 500 steps/day, if: age >65 years and/or chronic diseases and/or some restriction to increase physical activity (Tudor-Locke & Bassett 2004, Tudor-Locke, Washington & Hart 2009)	1. If baseline level <4 250, number of steps is increased 15% every other months until the target level is reached. In later phase this level is maintained or a new goal is set. 2. If baseline level >4 250, number of steps is increased 10% every other months until the target level is reached. In later phase this level is maintained or a new goal is set.

ORIGINAL PUBLICATIONS

I

THE EARLY CHANGES IN TRUNK MUSCLE STRENGTH AND DISABILITY FOLLOWING LUMBAR SPINE FUSION

by

Tarnanen S, Neva MH, Kautiainen H, Ylinen J, Pekkanen L, Kaistila T, Vuorenmaa M & Häkkinen AH, 2013

Disability and Rehabilitation 35, 134-139

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II

EFFECT OF ISOMETRIC UPPER EXTREMITY EXERCISES ON THE ACTIVATION OF CORE STABILIZING MUSCLES

by

Tarnanen SP, Ylinen JJ, Siekkinen KM, Mälkiä EA, Kautiainen HJ & Häkkinen AH,
2008

Archives of Physical Medicine and Rehabilitation 89, 513-521

III

CORE MUSCLE ACTIVATION DURING DYNAMIC UPPER LIMB EXERCISES IN WOMEN

by

Tarnanen SP, Siekkinen KM, Häkkinen AH, Mälkiä EA, Kautiainen HJ & Ylinen JJ, 2012

Journal of Strength and Conditioning Research 26, 3217-3224

IV

NEUTRAL SPINE CONTROL EXERCISES IN REHABILITATON AFTER LUMBAR SPINE FUSION

by

Tarnanen SP, Neva MH, Häkkinen K, Kankaanpää M, Ylinen J, Kraemer WJ, Newton RU & Häkkinen, AH, 2014

Journal of Strength and Conditioning Research 28, 2018-2025

V

RANDOMIZED CONTROLLED TRIAL OF POSTOPERATIVE EXERCISE REHABILITATION PROGRAM AFTER LUMBAR SPINE FUSION: STUDY PROTOCOL

by

Tarnanen S, Neva MH, Dekker J, Häkkinen K, Vihtonen K, Pekkanen L, & Häkkinen A, 2012

BMC Musculoskeletal Disorders 13, 123.

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Tarnanen *et al. BMC Musculoskeletal Disorders* 2012, **13**:123
http://www.biomedcentral.com/1471-2474/13/123

BMC
Musculoskeletal Disorders

STUDY PROTOCOL **Open Access**

Randomized controlled trial of postoperative exercise rehabilitation program after lumbar spine fusion: study protocol

Sami Tarnanen[1*], Marko H Neva[2], Joost Dekker[3], Keijo Häkkinen[4], Kimmo Vihtonen[2], Liisa Pekkanen[5] and Arja Häkkinen[1,6]

Abstract

Background: Lumbar spine fusion (LSF) effectively decreases pain and disability in specific spinal disorders; however, the disability rate following surgery remains high. This, combined with the fact that in Western countries the number of LSF surgeries is increasing rapidly it is important to develop rehabilitation interventions that improve outcomes.

Methods/design: In the present RCT-study we aim to assess the effectiveness of a combined back-specific and aerobic exercise intervention for patients after LSF surgery. One hundred patients will be randomly allocated to a 12-month exercise intervention arm or a usual care arm. The exercise intervention will start three months after surgery and consist of six individual guidance sessions with a physiotherapist and a home-based exercise program. The primary outcome measures are low back pain, lower extremity pain, disability and quality of life. Secondary outcomes are back function and kinesiophobia. Exercise adherence will also be evaluated. The outcome measurements will be assessed at baseline (3 months postoperatively), at the end of the exercise intervention period (15 months postoperatively), and after a 1-year follow-up.

Discussion: The present RCT will evaluate the effectiveness of a long-term rehabilitation program after LSF. To our knowledge this will be the first study to evaluate a combination of strength training, control of the neutral lumbar spine position and aerobic training principles in rehabilitation after LSF.

Trial registration: ClinicalTrials.gov Identifier NCT00834015

Keywords: Lumbar fusion, Disability, Pain, Quality of life, Spine, Exercise, Rehabilitation

Background

During the last 10 years there has been a significant increase in the number of lumbar spine fusions (LSF) [1]. The most common reasons for LSF are isthmic or degenerative spondylolisthesis, degenerative disc disease, and spinal stenosis [2]. In adult patients with lumbar isthmic or degenerative spondylolisthesis LSF has been reported to reduce symptoms [3,4]. However, the overall disability of patients after LSF may be high [5] and even 25% of patients rated the overall outcome as unchanged or worse in a 2-year follow-up study [3]. Most of the previous studies on LSF have evaluated the surgical procedure itself or compared conservative treatment to operative treatment. Less information is available on long-term exercise programs for patients after LSF surgery.

The effectiveness of rehabilitation after LSF has only been evaluated in four studies [6-9]. In these studies, the timing of the intervention has differed. In the studies of Nielsen et al. [8,9], prehabilitation started 6 to 8 weeks before surgery and continued during hospitalization. Abbott et al. [6] evaluated the effectiveness of psychomotor therapy implemented during the first 12 postoperative weeks. A Danish study [7] compared three different postoperative rehabilitation programs lasting between 12 and 20 postoperative weeks.

Exercise was an essential component of the rehabilitation protocols in all the LSF rehabilitation studies; however the guidance and exercise methods used were

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different. In the studies of Nielsen et al. and Christensen et al. [7-9], exercise programs included muscle endurance and strength training for the back and abdominal muscles, and cardiovascular conditioning. In the study of Abbott et al. [6], the exercise program consisted of motor relearning training of the transversus abdominis and multifidus, with cognitive and behavioral elements also integrated into the program. The results of these studies indicate that exercise may improve the outcome of LSF.

Typically, patients with lumbar isthmic or degenerative spondylolisthesis undergoing LSF have suffered low back pain for years and therefore may exhibit changes in the function [10] and structure of their trunk muscles [11], and in their cardiorespiratory condition [12]. LSF itself causes changes in the biomechanics of the lumbar spine, which may also accelerate degenerative changes in the adjacent segments [13] and cause muscle atrophy, leading to fatty infiltration of the lumbar muscles, especially in the multifidus[14-16]. As a possible consequence of these changes, low trunk muscle strength levels in patients after lumbar fusion have been reported [17,18].

The primary goals of the post-operative rehabilitation program are to control pain, decrease disability, restore back function, improve health related fitness and learn to use the low back during the healing process. Although the existing evidence supports the use of exercise in the rehabilitation of LSF patients, there is no consensus on the content of an exercise rehabilitation program after LSF. In addition, the durations of earlier interventions have been too short to achieve long-term changes in back function. Thus, there is a need to develop and test multifaceted rehabilitation programs to improve both back-specific and overall outcome after LSF. In contrast with previous exercise interventions for LSF patients, this study is novel in its development of a fusion-specific training program that takes into account changes in the biomechanics of the spine.

The main study questions are:

- Is combined back-specific and aerobic training more effective in decreasing back pain and disability than conventional instructions in postoperative rehabilitation?
- What are the effects of surgery and training on trunk muscle strength and mobility of the spine?
- What is the effect of fear of movement on post-operative exercise adherence, physical activity, pain and disability?

Methods/design

Study design

Figure 1 presents a flowchart of the study. The present randomized controlled trial will be conducted in Tampere University Hospital and the Central Finland Central Hospital. Approval of the study protocol was given by

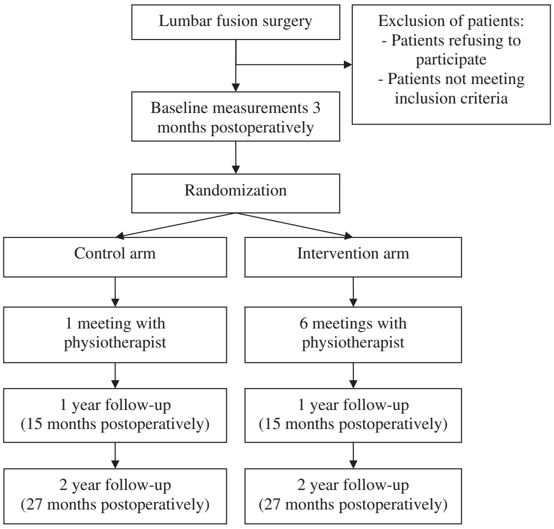

Figure 1 Flowchart of the study.

the Ethics Committee of the Central Finland Health Care District in 2008 (Dnro 4E/2008) and by the Ethics Committee of Tampere University Hospital in August 2008. Written informed consent will be obtained from all patients prior to participation.

Participants

Inclusion criteria

All patients aged over 18 years scheduled to undergo elective LSF surgery for isthmic or degenerative spondylolisthesis in Tampere University Hospital or the Central Finland Central Hospital are eligible for the study. Patients will be recruited by the spine surgeons in each hospital.

Exclusion criteria

Patients with severe cardiorespiratory or musculoskeletal disease, severe psychiatric/psychological disorder, extensive lower limb paresis, social reasons (alcohol abuse), and immediate complications after back surgery (infection) will be excluded from the study.

Surgery procedures

Spine surgeons will make the decision to operate according to their normal practice. The surgical procedure to be used is decompression and instrumented posterolateral fusion (PLF) with or without posterior lumbar interbody fusion (PLIF).

Randomization and blinding

After surgery, the participants will be randomized into either the combined back-specific (combination of strength training and training of control of the neutral lumbar spine position) and aerobic training arm or to the control arm. The allocation will be based on computer randomization in blocks of four patients. The randomization will be performed and the randomization lists maintained by the research nurses, who will not be involved in the assessment or treatment of the participants. The first list will be used to randomize the participants with isthmic spondylolisthesis and the second list to randomize those with degenerative spondylolisthesis. Both centres will have their own randomization lists. Assessors will be blind to the treatment group in both study centres. Physiotherapists will not be blind to group membership; instead, but both study arms will have their own physiotherapist who will carry out postoperative guidance. Blinding the patients to the allocation is not possible due to the nature of the intervention.

Preadmission clinic and early postoperative rehabilitation before the intervention

At the preadmission clinic, patients will meet with the spine surgeon, anesthesiologist, and physiotherapist, and be informed about the operation and rehabilitation. The early postoperative mobilization of the patients in the orthopaedic ward will be carried out by the physiotherapist. During the first three post-operative months, patients will be encouraged to walk and perform light abdominal, back, and thigh muscle exercises; stretching of hip muscles will also be included in the exercise program. The early postoperative exercise instructions will be similar for both study arms. The use of a bicycle ergometer will be allowed one month after the operation. Other types of exercise such as skiing, dancing, and water gymnastics will be permitted two months after surgery.

Study arms

The intervention arms will start three months postoperatively and will last 12 months.

Development of the intervention arm program

In the development of the protocol for the intervention arm, we have used information obtained from our own trunk muscle electromyography studies, conducted among healthy subjects [19,20] and lumbar fusion patients (Tarnanen et al., unpublished observation), other previously published studies on trunk and hip muscle activation during exercises [21-24], as well as information from a multidisciplinary group in the study hospitals (physiotherapists, nurses, spine surgeons), and feedback from patients regarding the feasibility of the program. The timing of the beginning of intervention is based on recovery from the surgery.

The back-specific exercise program has two main aims: (i) to improve control of the neutral lumbar spine position and (ii) increase trunk and hip muscle coordination, strength, and endurance [25-29]. (Table 1).

At the beginning of the program, trunk and hip muscle coordination and muscle endurance exercises will be performed in a prone, supine and four-point kneeling position. During the intervention the performance positions will gradually become more functional [30] and the loads increase progressively up to 50-70% of the repetition maximum to optimize muscle strength and muscle mass development. A subset of these exercises will be carried out with light loads to improve explosive force (high-velocity repetitions) and movement control. In addition, muscle-fatiguing training will be used for the back muscles to produce regional increases in blood flow capacity among the muscle fibers that experience increased activity during loading. Participants will be instructed to perform home exercises at least 2–3 times per week.

The aerobic walking program has three aims: (i) to increase the total amount of physical activity [31], (ii) improve patients' aerobic capacity, and (iii) increase muscle

Table 1 Back-specific exercises program

Phase	Back specific exercises	Goal of the exercise
I	1. Squat (SP, EB)	MS
	2. Abdominal crunch (SUP)	ME
	3. Hip abduction (CLP)	CNSP
	4. Hip abduction and external rotation (SLP, EB)	CNSP/ME
	5. Hip extension (PRO)	CNSP
	6. Hip extension (FPKP, EB) Sets x Repetitions: 2 x 10-15-20	CNSP/ME
II	1. Squat (SP, EB)	MS
	2. &3. Bilateral shoulder extension and flexion (SP, EB)	ME/MS
	4. Heel slide or leg lift and knee extension with one leg (SUP)	CNSP
	5. Hip extension or hip extension and knee extension (CLP)	CNSP/ME
	6. Hip abduction (SLP, EB)	CNSP/ME
	7. Hip extension (EB) or bird dog exercise (FPKP) Sets x Repetitions: 2 x 10-15-20	CNSP/ME
III	1. Squat (SP, EB)	MS
	2. & 3. Bilateral shoulder extension and flexion (SP, EB)	ME/MS
	4. Leg lift and knee extension with one leg (SUP)	CNSP
	5. Hip extension and knee extension (CLP)	CNSP/ME
	6. Bird dog exercise (FPKP)	CNSP/ME
	7. Hip abduction (SP) Sets x Repetitions: 2–3 x 10-15-20	CNSP/ME
IV	1. Squat (EB) or forward lunge (SP)	MS
	2. Waiters bow exercise with elastic band (SP, EB)	MS
	3. & 4. Bilateral shoulder extension and flexion (SP, EB)	ME/MS
	5. & 6. Unilateral shoulder horizontal adduction and abduction (SIP, EB)	CNSP/ME
	7. Hip abduction (SP, EB) Sets x Repetitions: 2–3 x 10-15-20	CNSP/ME
V	1. Forward lunge (SP)	ME/MS
	2. Waiters bow exercise (SP, EB)	MS
	3. & 4. Unilateral shoulder horizontal adduction and abduction (SP, EB)	CNSP/ME
	5.& 6 Downward chop and upward chop (SIP, EB)	CNSP/ME
	7. Hip abduction (SP, EB) Sets x Repetitions: 2-3-4 x 10-15-20	CNSP/ME
VI	1. Forward lunge (SP)	ME/MS
	2. Waiters bow exercise (SP, EB)	MS
	3. & 4. Unilateral shoulder horizontal adduction and abduction (SP, EB)	CNSP/ME
	5. & 6. Downward chop and upward chop (SP, EB) Sets x Repetitions: 2-3-4 x 10-15-20	CNSP/ME

SP, standing position; SUP, supine position; CLP, crook lying position; SLP, side lying position; PRO, prone position; FPKP, four-point kneeling position; SIP, sitting position; EB, with elastic band resistance; MS, muscle strength; ME, muscle endurance; CNSP, control of the neutral lumbar spine position.

capacity for fatty acid oxidation [32,33]. The program includes a progressive increase in the number of steps and interval walking workouts.

The total activity level will be evaluated during the first week by pedometers. Based on this information, patients will be instructed to increase their activity level progressively and monitor the amount of daily steps with the pedometer. (Table 2). Interval walking will be added to the exercise program four months after the beginning of the intervention. Each interval exercise consists of 5–10 minutes warm-up at normal walking speed, followed by periods of 30s - 1 min of brisk walking and 3 min of walking at normal speed alternated four times. The total length of the exercise bout will be 25–30 minutes. The length and intensity of brisk walking will be gradually increased during the last eight months.

Individual guidance sessions with the physiotherapist will be started three months after the LSF, with booster sessions every second month thereafter. In each session the physiotherapist will give guidance on the exercises to be performed in the next training phase and check the patients' exercise techniques. In addition, patients will be given a leaflet containing written and pictorial information about the exercises. Each patient will perform the training independently at home; however, the progression of the exercises will be checked with the physiotherapist. During the first session, patients will fill in a personal exercise contract form and set their

Table 2 Aims for increasing the number of daily steps

Aim	Model of progression
10 000 steps/day, if: age under 65 years, healthy and no restrictions to increase physical activity	1. If baseline level <5 000 (sedentary), number of steps is increased 15% every other months until the target level is reached
	2. If baseline level 5 000–7 499 ("low active"), number of steps is increased 10% every other months until the target level is reached
	3. If baseline level 7 500–9 999 ("somewhat active"), number of steps is increased 5% every other months until the target level is reached
	4. If baseline level >10 000 (active), this level is maintained or number of steps is increased 5% every other months until 12 500/day ("highly active") is reached (Categorized according to Tudor-Locke et al. 2008 [34])
7 500 steps/day, if: age >65 years and/or chronic diseases and/or some restriction to increase physical activity [35,36]	1. If baseline level <4 250, number of steps is increased 15% every other months until the target level is reached. In later phase this level is maintained or a new goal is set.
	2. If baseline level >4 250, number of steps is increased 10% every other months until the target level is reached. In later phase this level is maintained or a new goal is set.

personal goals [37]. Goals will be reassessed in the middle phase of the intervention. Possible barriers to exercise (e.g. kinesiophobia) will be identified [38,39]. If a patient's score on the Tampa scale for kinesiophobia (TSK) is over 37 in the post-operative assessment, the physiotherapist will explain to the patient (during the second/third guidance session) how and why some individuals with low back pain may develop a chronic pain syndrome (the fear-avoidance model, [40]). The patient's experiences of the previous training phase will be reviewed during each guidance sessions. Patients will receive elastic bands (Thera-Band, The Hygenic Corporation, Akron Ohio, USA) and a pedometer (Omron Walking Style II, Kyoto, Japan) for their personal use.

Control arm

Patients randomized to the control arm will be managed according to normal hospital rehabilitation practice. Three months postoperatively patients will receive instructions for home exercises in a single individual guidance session. The exercise program will consist of light muscle endurance (abdominal crunch, bird dog exercise, forward lunge, posterior pelvic tilt), mobility (hamstring stretch, lateral flexion of thoracic spine), and balance exercises (one-leg standing). Patients will be instructed to perform the home exercises 3 times per week.

Outcomes

The outcome measurements will be assessed at baseline (3 months postoperatively), at the end of the exercise intervention period (15 months postoperatively), and after a 1-year follow-up. Only primary outcome variables will be used in the 27 months follow-up assessment.

Primary outcome variables

The intensity of back and lower limb pain during rest and daily activities in the past week will be assessed by means of the visual analogue scale (VAS) [41]. Disability due to back pain during the past week will be assessed by the Finnish version of the Oswestry Low Back Pain Disability Questionnaire 2.0 [42]. Quality of life will be evaluated by the Finnish version of the generic SF-36 Health Survey Questionnaire [43].

Secondary outcome variables

Physical function/fitness Maximal isometric forces of the trunk flexors and extensors will be measured using a strain-gauge dynamometer [44]. Endurance strength of the trunk extensors will be measured by the Biering-Sorensen test [45,46]. Spinal mobility towards flexion will be measured by the Schober and Stibor tests [47] and fingertip–floor distance tests [45], and lateral bending by the method described by Frost et al. [48]. The intensity of pain during the trunk muscle strength and mobility measurements will be assessed with a VAS. The 'timed up and go' test (TUG) will be used to assess functional mobility (power, walk velocity, agility and dynamic balance) [49].

Kinesiophobia The TSK will be used to measure the subjective experience of fear of movement [50].

Assessment of physical activity and exercise adherence The amount of physical activity will be evaluated by the short form of the International Physical Activity Questionnaire (IPAQ) [51]. Training diaries will capture the frequency of the back-specific exercises and pedometers will be used to assess the total amount of daily steps in the intervention arm. The number of aerobic steps (10 minutes of continuous walking more than 60 steps per minute) during one week will be reported at least every second month.

Statistical analysis

Sample size

Cristensen et al. [7] estimated that a sample of ~60 patients (30 per group) is necessary to achieve 85% power for detecting a 25% difference in disability over time (baseline to 1 year), or at a follow-up of a 1 year, with a one-sided significance α-level of 0.05. However, we assume the between-group difference in pain will be lower in our participants. Assuming a dropout rate of 15-20% at the 1-year follow-up, we aim to include at least 80 patients (preferably 100) in our sample.

The clinical outcome variables will be analyzed by the intention-to-treat principle with the last observation carried forward (LOCF). The normality of variables will be evaluated by the Shapiro-Wilk statistic. Statistical comparison between the arms will be done using the chi-square test, Fisher's exact test, bootstrap-type analysis of covariance (ANCOVA) or multivariate analysis of variance (MANOVA) with Pillai's trace statistics. A multiple imputation (Markov-chain Monte Carlo) method will be applied to supply possible missing values of individual questionnaire items, when appropriate.

Discussion

This paper describes the rationale and design of a study which will assess the effectiveness of long-term combined back-specific (combination of strength training and training of control of the neutral lumbar spine position) and aerobic training in post-operative rehabilitation after lumbar spine fusion. Previous studies evaluating rehabilitation after LSF surgery are short-term and mostly focus on a specific type of exercise. However, trunk muscle function and health related fitness in patients with chronic low back pain are often so extensively impaired that more comprehensive training is probably needed. The effectiveness of exercise interventions are partly adherence-dependent, and thus special attention will be paid to patients goal setting, monitoring of progression and motivation. The selection of patients aims to reflect the patient population which usually undergoes this operation, and hence we will not be applying any strict exclusion criteria concerning age or comorbidities. This will improve the generalizability and implementability of the results. The results will have practical value in the planning and development of treatment options after lumbar spine fusion.

Abbreviations

LSF: Lumbar spine fusion; VAS: Visual analogue scale; TSK: Tampa scale for kinesiophobia.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

ST, MHN, JD, KH, KV, LP and AH were responsible for the design of the study. All authors were involved in drafting the manuscript and revising it for critically important content. All authors have read and approved the final manuscript.

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