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Chapter 1

General introduction

This thesis focuses on bringing the study of spinal loading during tasks such as manual lifting from the laboratory setting to the field. In this general introduction an overview will be given of the literature that forms the basis of this thesis. First, the medical and economical impact of low back pain (LBP) on society, and the pathophysiology of LBP are discussed. Then, the epidemiological literature providing evidence for mechanical load on the spine as a risk factor for low back pain is reviewed. In the following section, it is discussed how the magnitude of mechanical loading of the spine during physical work (e.g. during manual lifting) could lead to spinal injury. Next, a short overview of the literature that studied the effect of manual lifting on spinal loading is provided. Finally, an outline of the subsequent chapters of the thesis is given.

LBP in society

LBP is still a major medical as well as an economical problem in industrialised nations (Maetzel & Li, 2002; Goetzel et al., 2003; Dagenais et al., 2008). In the general population, it has been reported that 70–85% of all people experience LBP at some time in life and that LBP is responsible for about 12% of all sick days (Andersson, 1999). In the Netherlands, LBP was the most common self-reported musculoskeletal disorder in 1998 with an annual prevalence of 43.9% (Picavet & Schouten, 2003) and in 1991 the cost to society was estimated to be as much as 1.7% of the gross national product (van Tulder et al., 1995). Furthermore, prevalence rates of LBP have been reported to be higher in non-sedentary workers than in sedentary workers (Hildebrandt, 1995; Holmström & Engholm, 2003), which indicates that work-related risk factors may play a role in the aetiology of LBP.

Tissue origin of LBP

When standard diagnostic techniques are utilised, in only about 10% of the LBP patients a specific diagnosis can be made regarding the pathophysiological cause of the pain (e.g. hernia nuclei pulposi, infection, osteoporosis, rheumatoid arthritis, fracture, or tumour). In the remaining 90% of the patients, the nonspecific LBP patients, the pathophysiological cause of LBP remains unknown (Koes et al., 2006).

One explanation could be that there is no pathophysiological cause of LBP in these patients. An alternative explanation for the negative findings might be that standard diagnostic techniques (e.g. x-ray) do not detect important abnormalities of the spine.

The latter explanation is supported by several studies employing more advanced diagnostic techniques such as discography, showing damage in a majority of the LBP patients (Grubb et al., 1987; Vanharanta et al., 1987). Furthermore, structural damage appears to be a quite specific finding for LBP patients by itself and highly specific when appearing in combination with provocation of pain on mechanical stimulation of the intervertebral disc (Walsh et al., 1990; Schwarzer et al., 1995; McNally et al., 1996; Manchikanti et al., 2001).

Other evidence that LBP originates from specific tissues of the spine (Figure 1-1) emerges from a study by Kuslich et al. (1991). During surgery for LBP, several spinal structures were mechanically stimulated and the resulting pain sensation was evaluated. The following structures were most frequently reported to result in LBP resembling the usual LBP in these patients: the outer annulus fibrosus (33%–71%), the endplates (33%–61%), the facet joints (15%–30%) and the interspinous and supraspinous ligaments (6%–25%).

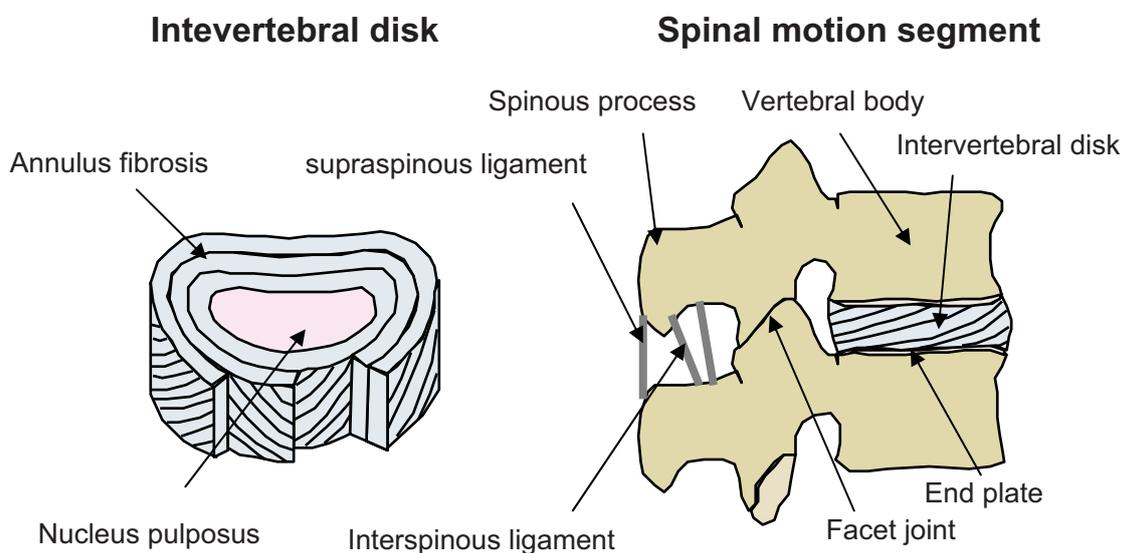


Figure 1-1. Schematic overview of spinal structures

Finally, post mortem studies have shown that (repaired) damage to endplates, which is usually not visible with x-ray and other imaging methods (Malmivaara et

al., 1987), is a very common phenomenon (Coventry et al., 1945; Vernon-Roberts & Pirie, 1973; Hilton et al., 1976).

In conclusion, the above mentioned studies suggest that with more advanced diagnostic methods, that are not routinely applied in the standard diagnostic process, damage to the spine could be detected in the majority of LBP patients. In a substantial part of the population studied with such techniques, the pain appeared to originate from the intervertebral disc (annulus fibrosus) and the endplate.

Epidemiologic evidence for mechanical loading of the spine as a risk factor for LBP

It is assumed that the origin of LBP is multifactorial since epidemiologic studies have identified many risk factors for LBP. Numerous reviews have reported on these risk factors which can be divided in: 1) personal risk factors, e.g. age, gender, smoking and body weight (Dempsey et al., 1997; Goldberg et al., 2000; Leboeuf-Yde, 2004; Manek & MacGregor, 2005; Hamberg-van Reenen et al., 2007; Wai et al., 2008); 2) psychosocial risk factors, e.g. job satisfaction, social support and job control (Hoogendoorn et al., 2000b; Hartvigsen et al., 2004; Macfarlane et al., 2009); 3) physical risk factors, e.g. manual lifting, pushing and pulling, whole body vibrations and awkward postures (Ferguson & Marras, 1997; Bovenzi & Hulshof, 1999; Hoogendoorn et al., 1999; Kuiper et al., 1999; Lötters et al., 2003; Lis et al., 2007; Bakker et al., 2009; Chen et al., 2009; Roffey et al., 2009, in press).

Because this thesis is based on the assumption that high mechanical loading of the spine due to physical factors is a potential cause of LBP, evidence from epidemiological literature regarding this assumption will be discussed in more detail. Two systematic reviews found consistent evidence for manual lifting and frequent trunk bending and twisting as risk factors for LBP. For heavy physical work in general, carrying and pushing and pulling conflicting results were reported (Kuiper et al., 1999; Lötters et al., 2003). A limitation of the above mentioned reviews is that the conclusions were mainly based on results of cross-sectional studies, which provide evidence for a relationship, but not for a causal relationship between risk factors and LBP. Therefore, other systematic reviews have been carried out, considering mainly longitudinal studies, which provide stronger

evidence for a causal relationship. In accordance with the previously mentioned reviews, Hoogendoorn et al. (1999) found “strong evidence” for manual materials handling (mainly concerning lifting) and trunk bending and twisting and “moderate evidence” for heavy physical work in general as risk factors for LBP. In accordance with the latter conclusion, a review based on more recent longitudinal epidemiological studies (Bakker et al., 2009) concluded that there was “conflicting evidence” for heavy physical work as risk factor for LBP. However, in contrast to Hoogendoorn et al. (1999), this review also reported “conflicting evidence” for manual materials handling (including manual lifting) and trunk bending and twisting as risk factors for LBP. Yet, when focusing on the details of the individual studies, it becomes apparent that the lack of significance of the associations could, in most cases, have been a result of methodological limitations. An important limitation of most studies is that they failed to quantify the magnitude or duration/frequency of exposure, or both, resulting in an inadequate characterisation of (cumulative) spinal loading. Another limitation of some of these studies is that, even if reported, the range in exposure was small, possibly resulting in effects that were too small to be detected. Last but not least, in almost all studies discussed in the review (Bakker et al., 2009), the information on exposure was collected by means of self-report, of which the accuracy and precision has been shown to be low (van der Beek & Frings-Dresen, 1998). Accordingly, NIOSH (Bernard, 1997) reported stronger associations between physical exposures and LBP if exposures were assessed more objectively. Only in one prospective study (Hoogendoorn et al., 2000a) mentioned in the review of Bakker et al. (2009), the magnitude and frequency/duration of physical exposures were assessed more objectively, by an observer analysing video recordings of the subjects during their work and by measuring the weight of the objects handled. This study reported a significant relation with LBP of working >5% of the time with a trunk flexion >60° and of lifting loads >25kg >15 times/8-h working day. Curiously, Bakker et al. (2009) concluded that no effect was found, referring only to the multivariate analyses that were additionally performed in the study. These multivariate analyses resulted in non-significant effects (although trends were still clear), because not all subjects could be included and because the Cox regression produced, according to the authors, “too conservative” estimates of the confidence intervals. Because of this and since the multivariate analyses yielded

similar results as the univariate analyses, Hoogendoorn et al. (2000a) based their conclusions on the univariate analyses.

It is striking, when contemplating all the literature mentioned in the systematic reviews, that while most of the epidemiologic studies were designed to test the hypothesis that mechanical load of the spine causes LBP, almost none of the studies actually estimated mechanical spinal loading. Instead, they reported separate, usually self-reported, aspects of the work that could contribute to high mechanical spinal loading, e.g. trunk flexion and heavy lifting. Because the total spinal loading is the sum of the spinal loading caused by the trunk movement (e.g. trunk flexion) and the external forces (e.g. lifting), it would be better to consider these variables simultaneously in a biomechanical analysis. Surprisingly, only two epidemiologic studies actually quantified spinal loading. In a case-control study, Punnett et al. (1991) assessed peak spinal compression forces in automobile assembly workers. Although a strong relationship was found between LBP and non-neutral trunk postures (e.g. trunk flexion), no relation was found between LBP and peak spinal compression forces. However, limitations of this study were that a static biomechanical model was used and that the spinal loading of a subject was characterised by a single peak compression value, i.e. no measures of cumulative loading were calculated. In a more recent case-control study reported in two papers (Norman et al., 1998; Kerr et al., 2001), a more sophisticated quasi-static biomechanical model (including measured “dynamic” external hand forces) was used and besides peak spinal loading, cumulative spinal loading was quantified as well. This study found a significant relation between LBP and cumulative as well as peak spinal loading (both compression and shear forces). The reason why direct estimates of spinal loading were quantified in only two epidemiologic studies is probably because the methods for the assessment of spinal loading at the workplace that were applied in epidemiological studies (video analysis + force measurements) are extremely labour intensive. New, more automated measurement methods are warranted to allow for easy application of biomechanical models in future epidemiologic studies, especially when one wants to measure (dynamic) spinal loading continuously throughout the day (during work and leisure time).

In summary, early reviews based on cross-sectional, case-control and longitudinal studies reported “strong evidence” for manual lifting and trunk bending and twisting as risk factors for LBP. A more recent review based on solely longitudinal epidemiological studies reported “conflicting evidence” for these exposure measures. However, most of the non-significant findings could be explained by inadequate characterisation of exposure (no magnitude and/or frequency/duration of exposure measured). Additionally, in almost all of the studies exposure estimates were obtained by means of self-reports of which the accuracy and precision has been shown to be low. Furthermore, only two epidemiological (case-control) studies investigated the relationship between estimated spinal forces and LBP, of which only the more recent study, using a more sophisticated biomechanical method to calculate spinal loading, found significant associations. More studies are needed to confirm these results. The above stresses the need for new prospective studies using adequate estimates of spinal loading. Because the methods which have been used up to now to estimate spinal loading objectively (e.g. video analysis) are too labour intensive to be applied in large scale studies, new automated measurement methods should be developed that allow for easy and continuous assessment of spinal loading at the workplace.

Mechanical loading and spine injury

As discussed in the previous section, epidemiological literature has identified manual lifting and trunk bending and twisting as risk factors for LBP. This is probably because manual lifting and trunk bending and twisting can result in high mechanical loading of the spine which can lead to spinal damage. Below, possible mechanisms by which mechanical spinal loading due to trunk bending and twisting and manual lifting could lead to the spinal damage will be discussed.

In most epidemiological studies trunk posture is not clearly defined. For example, it is often unclear whether trunk bending refers to pure bending (spinal flexion) or to the angle of the trunk segment with the vertical (trunk inclination). When people “bend over” during work this usually involves trunk inclination as well as spinal bending. Inclination of the trunk has a major effect on spinal forces because, when the trunk is inclined, the spine is not only loaded by the forces caused by the upper body weight and accelerations (net reaction forces), but also by the trunk

muscle forces, which have to generate the required spinal moments. Muscle forces are usually much higher than the net reaction forces. For example, when an average male bends over to ground level, net reaction forces usually remain around 500 N, whereas the total spinal forces may reach 3500 N (Hoozemans et al., 2008). This load magnitude might already cause spinal damage in some subjects, as it is in the range of the *in vitro* spinal strengths reported in the literature (2000-10000 N) (Hansson et al., 1980; Brinckmann et al., 1989). The strength of spinal motion segments has been reported to be even lower under repetitive loading (Liu et al., 1983; Hansson et al., 1987; Brinckmann et al., 1988). In these *in vitro* studies, where spinal motion segments were loaded in a neutral position, endplate fractures were found in most of the cases while the intervertebral disc usually remained intact.

A number of studies showed that loading the spine in bent postures, causing tensile stressed in the ligaments and lamellae of the intervertebral disc, can result in damage to the intervertebral disc. Whereas this does not seem to be the case for a single maximal loading cycle of a spinal motion segment in a flexed posture (Adams & Hutton, 1982, 1986), damage to the annulus fibrosus is a more common finding when the spinal motion segment is repeatedly loaded in a bent position (Adams & Hutton, 1985; Callaghan & McGill, 2001), especially in asymmetric postures (Gordon et al., 1991; Drake et al., 2005).

Twisting or torsion of a spinal motion segment has been assumed to cause shearing between lamellae of the annulus fibrosus, which could lead to damage to the intervertebral disc. While twisting a spinal motion segment once until failure probably leads to damage to the facet joint rather than to the disc (Adams & Hutton, 1981), exposure to repeated twisting has indeed been shown to result in damage to the annulus fibrosus (Farfan et al., 1970; Liu et al., 1985; Drake et al., 2005).

Lifting often involves trunk inclination and spinal bending and twisting, which, as described above, could damage the spine. Moreover, during manual lifting the spine is additionally loaded due to the external load. In *in vivo* experiments compression forces have been estimated to reach up to 5000 N when lifting objects from ground level (Faber et al., 2009b). Considering the *in vitro* spinal strength mentioned before (2000-10000 N), forces of this magnitude can easily damage the spine.

In conclusion, results from *in vitro* studies render it plausible that the spinal forces and postures involved in trunk bending and twisting and manual lifting can result in damage to structures of the spine, comparable to the type of damage that has been reported in LBP patients when using in-depth diagnostic techniques.

Short review of laboratory studies investigating the effects of ergonomic interventions on spinal loading in manual lifting

As described earlier, epidemiologic literature suggests that high mechanical spinal loading caused by trunk bending and twisting and manual lifting may be an important cause of LBP. Furthermore, *in vitro* studies showed that mechanical loading of the spine involved in trunk bending and twisting and in manual lifting can cause damage to the spine that is typical for LBP patients. In lifting, the spinal forces are relatively high compared to other tasks (Nachemson & Elfstrom, 1970), and can easily exceed the *in vitro* strength of the spine (Brinckmann et al., 1988; van Dieën & Toussaint, 1997). Therefore, especially lifting tasks have received much attention in the literature. Because invasive methods are needed to directly measure spinal forces (Nachemson & Morris, 1963), only a few studies have applied this method during manual lifting (Nachemson & Elfstrom, 1970; Wilke et al., 1999; Wilke et al., 2001). In most other studies, spinal forces have been estimated by employing biomechanical models. Most studies have used spinal moments as a measure of spinal loading because these moments are highly related to spine compression in lifting (van Dieën & Kingma, 2005). Some other studies estimated spinal forces with (EMG-assisted) trunk models. Because application of these methods in field studies is difficult, most of the studies were carried out in the laboratory environment. The focus of many of these studies is the relation between task variables and spinal loading during manual lifting. Results from these laboratory studies provide potential targets for ergonomic interventions regarding manual lifting. These targets can be subdivided in three groups: 1) initial object position (vertical and horizontal position), 2) object characteristics (mass, size, handles vs. no handles and unexpectedly heavy/light mass) and 3) lifting strategy (lifting technique, load tilt, one-handed vs. two-handed lifting, team lifting and symmetric vs. asymmetric lifting). In the following sections an overview of the

laboratory studies regarding the effects of these task variables on spinal loading will be provided.

Initial object position

The initial position from which an object is lifted is an important determinant of peak spinal loading as peak loading usually occurs slightly after lift-off. Especially initial vertical load position has a large effect because it strongly affects the amount of trunk inclination used during a lifting task which, given the high mass of the trunk segment, has a major effect on the spinal moments that have to be generated by the trunk muscles (Marras et al., 1997, 1999b; Ferguson et al., 2002; Lavender et al., 2003; Hoozemans et al., 2008).

The first studies investigating the effect of initial horizontal load position on spinal loading did this with boxes that were lifted from floor level (Schipplein et al., 1995; Lavender et al., 1999). Effects were significant, but smaller than the previously reported effects of initial vertical position. This is probably because, when lifting from near ground level, the initial horizontal load position does affect the spinal moment caused by the object lifted, but barely affects the moment caused by trunk inclination. More recent studies found that the effect of initial horizontal load position was substantially larger for objects that are lifted from higher initial load positions (Marras et al., 1997, 1999b; Ferguson et al., 2002), probably because in this situation the initial horizontal load position has a substantial effect on the spinal moments caused by trunk inclination.

Object characteristics

Of the object characteristics studied previously, load mass in particular has received much attention because it is an obvious target for an ergonomic intervention. A number of studies reported a significant effect of load mass on spinal loading (Buseck et al., 1988; Schipplein et al., 1990; Potvin et al., 1992; Schipplein et al., 1995; Fathallah et al., 1997; Marras et al., 1997; Lavender et al., 1999; Marras et al., 1999b; Davis & Marras, 2000; Ferguson et al., 2002; Hoozemans et al., 2008). However, as an ergonomic intervention, load mass reduction seems less effective than optimising working height (de Looze et al., 1996; Marras et al., 1997, 1999b; Hoozemans et al., 2008).

The size of the load also has been shown to affect spinal loading. Larger loads usually result in higher spinal loading than small loads (Garg & Herrin, 1979; Kingma et al., 2004; Kingma et al., 2006). One important reason for this effect is that the centre of mass of a larger load is located further from the body, resulting in a larger moment arm of the load. Another reason is that, when lifting a load that is very wide, it is more difficult to lift it close to the body. This is especially the case when lifting in a squatted posture (Garg & Herrin, 1979; Kingma et al., 2004; Kingma et al., 2006).

Providing handles on objects so that people do not have to reach for the bottom of the load, has been shown to result in reduced trunk flexion, resulting in decreased spinal loading (Davis et al., 1998). Only when boxes were lifted from a height above 90 cm, handles did not affect spinal loading, probably because, regardless of the presence of handles on the object, subjects did not have to bend forward to reach for the load.

Incorrect anticipation for load mass, i.e. underestimating or overestimating the mass, has been suggested to increase spinal loading. While it has been reported that mass overestimation (lifting a unexpectedly light load) leads to an increased peak spinal loading (Commissaris & Toussaint, 1997), mass underestimation does not have a significant effect on spinal loading (van der Burg et al., 2000).

Lifting strategy

Lifting technique has been a topic of many studies. The squat technique (knees bent, trunk extended) is usually advised by practitioners because it is assumed that this technique results in the lowest spinal loading. Many studies have compared squat lifting to stoop lifting (knees extended, trunk bent). In 1999, a review was published (van Dieën et al., 1999a) in which it was concluded that the differences between stoop and squat lifts were generally small and that squat lifting did not consistently result in the lowest spinal loading. More recent studies concluded that the effect of lifting technique is dependent on the lifting condition (Kingma et al., 2004; Kingma et al., 2006). For example, a squat technique resulted in lower spine loads than a stoop technique, when a box was lifted at its handles from a position between the knees. However, the effect of lifting technique was opposite when a load without handles was lifted from a position in front of the knees, which,

especially in the squat lifts, resulted in a large moment arm of the load relative to the lumbar spine.

Only a few studies investigated the effect of load tilt on spinal loading. In symmetric lifting no significant effect of load tilt towards the body was found (Gagnon, 1997), whereas, in asymmetric lifting, lifts involving tilting resulted in somewhat smaller peak spinal moments than lifts without tilting (Gagnon et al., 2000).

Performing one-handed lifting instead of two-handed lifting has been shown to reduce spinal loading when performing asymmetrical lifts using the hand at the side of the body where the load is located (Marras & Davis, 1998; Kingma & van Dieën, 2004). Further decrease in spinal loading can be achieved when the free hand is used to support the weight of the upper body (Ferguson et al., 2002; Kingma & van Dieën, 2004). In symmetrical lifts no differences were found between one- and two-handed lifts (Marras & Davis, 1998; Ferguson et al., 2002).

To date, studies investigating the effects of team lifting have only compared one-person lifts with a two-person team lifts, where loads in the two-person lifts were twice as heavy as in the one-person lifts. For symmetrical team lifts, substantial reductions of spine load were found (Dennis & Barrett, 2002). However, no effects were found in asymmetrical team lifts (Marras et al., 1999a).

A number of studies compared symmetrical to asymmetrical lifts. As expected, asymmetrical spinal moments were found to increase when the lift became more asymmetric, but no effects were found for the total spinal moments (Plamondon et al., 1995; Kingma et al., 1998). For spinal forces calculated with an EMG-driven trunk model, one research group has consistently reported higher spinal compression forces in asymmetrical lifts (Fathallah et al., 1998; Marras & Davis, 1998; Davis & Marras, 2005). However, because in those studies no spinal moments were reported, it remains unclear why the amount of asymmetry increased spinal forces. In addition, results from another research group suggest that the asymmetry of the lift does not lead to higher spinal compression forces (van Dieën & Kingma, 1999b, 2005). Further research is required to understand these conflicting results.

Aims and outline of the thesis

The focus of this thesis is on bringing the study of spinal loading during tasks such as manual lifting from the laboratory to the field. Three questions emerge in this context. The first is whether results from the large number of laboratory studies can be generalised to the field. The second question is to what extent two currently available methods to assess spinal loading can be applied in the field. Because of limitations of the measurement techniques used in previous epidemiological studies and in the two field studies described in this thesis, the third question is how new technology, which suffers less from these limitations, can be made suitable for (large scale) studies of manual lifting in the field. The thesis can be roughly subdivided in three sections, each focussing on one of these questions.

Chapters 2 & 3. Generalisability of results of typical laboratory studies

The first section, consisting of two chapters, investigates whether the results of typical laboratory studies (a literature review is provided above) can be generalised to the field.

In the study described in **chapter 2**, experienced construction workers participated in an experiment in which the effects of two ergonomic interventions (i.e. block mass reduction and increase of lifting height) on spinal loading were tested in a depalletising lifting task that the workers frequently perform during a normal working day. Construction workers were free to lift the building blocks the way they usually do at the workplace. The aim of this study was to find out whether, in this unconstrained lifting task performed by experienced workers, the effects of the ergonomic interventions were different from the effects reported previously based on typical laboratory studies, in which usually non-professional lifters performed more constrained lifting tasks.

Chapter 3 describes a study in which the effect of the type of lifting task and the effect of lifting experience were investigated. To this end, a group of inexperienced subjects performed lifts from a close and far initial horizontal position. They first did this in a typical laboratory lifting task in which the box was not transported to another location. After this lifting task, subjects repeated the lifts in a more realistic lifting task in which they transported the box to a location at a few meters

distance. Subsequently, subjects received a short training in which they were familiarised with different working methods (e.g. shifting and tilting), after which they repeated the more realistic lifting task.

Chapters 4 & 5. Application of two currently available measurement methods to assess spinal loading in the field

From the first two studies it was concluded that results from typical laboratory studies could not directly be generalised to the field and that, therefore, it would be better to study the effect of ergonomic interventions at the workplace using subjects familiar with the work task. Therefore, in the second section of the thesis, two field studies are described applying two currently available measurement methods to assess spinal loading in the field. In **chapter 4**, a field study is presented in which the effect of ship motion on spinal loading was investigated. In this study spinal loading was assessed using our standard laboratory measurement system (i.e. force plate and optoelectronic and EMG measurement systems), which was installed in the lunchroom of a training vessel of the Royal Netherlands Navy. Subjects, experienced with working on a ship, performed lifts under a wide range of sailing conditions, while spinal loading as well as ship motion were measured. In **chapter 5**, a much more simple method was used to estimate spinal loading in construction workers performing a range of tasks at the workplace, identical to the ones that were performed in the experiment described in chapter 2. For each block handled, the horizontal and vertical positions of the block relative to the midpoint between the ankles were obtained using a simple tape-measure. These measures were used in a previously developed regression equation to estimate spinal loading (Potvin, 1997). Outcomes of these measurements were compared to the outcomes of the laboratory study reported in chapter 2.

Chapters 6, 7 & 8. Development of new ambulatory measurement tools for the assessment of spinal loading in the field.

Because most studies that attempted to assess spinal loading in the field, including the two field studies described in this thesis, had significant limitations, the last part of this thesis explores new measurement methods using recently developed body mounted measurement techniques. The advantage of these new

measurement methods over the methods applied in chapters 4 and 5 is that subjects can perform their work in an unconstrained manner and the digitally recorded data is easily captured and directly available after the measurement.

In **chapter 6**, a simple method is described to measure trunk inclination using a single body-mounted inertial/magnetic sensor (IMS). Because the trunk is not a rigid segment, it is not obvious where to place such an IMS on the trunk. Therefore, this study investigated at which position an IMS should be placed on the trunk in order to get an optimal estimate of the trunk inclination.

In **chapter 7**, a study is described in which an ambulatory method was employed for measurement of 3D ground reaction forces using instrumented force shoes. In this study the performance of these force shoes in assessing ground reaction forces and ankle and L5/S1 moments was investigated in a large variety of tasks (lifting, pushing and pulling and walking tasks).

IMs measuring kinematics of lower body segments and force shoes measuring ground reaction forces could potentially be used for bottom-up calculated lower body joint moments. Because IMs can only measure orientation of segments, the positions of segments relative to each other and relative to the ground reaction forces have to be determined by linking them, while assuming fixed segment lengths and zero joint translation. In **chapter 8** lower body joint moments were estimated during manual lifting using a bottom-up linked segment model based on segment orientations only. Furthermore, joint moments were synchronously measured with our standard laboratory measurement system. The outcomes of the two analysis methods were compared.

Finally, in **chapter 9**, an overview of the results of studies in this thesis is provided. Furthermore, implications of these studies for practice and future research are discussed.

