Chapter 1

General Introduction

LOW-BACK PAIN IN SOCIETY

In our society, low-back pain (LBP) is one of the most common health problems, thereby causing a large burden, medically as well as economically (Goetzel et al., 2003; Maetzel & Li, 2002). As a specific pathological diagnosis is not made in many cases of LBP (Koes et al., 2006), LBP is often labeled as non-specific. In this thesis, when mentioning LBP, we refer to self-reported LBP, without focusing on diagnoses.

While data differ considerably between studies executed in different countries, lifetime LBP prevalence worldwide is estimated to be approximately 39% while the point prevalence is estimated to be around 19% (Hoy et al., 2012). In the Netherlands, the point prevalence of LBP was estimated to be 26%, depicting that more than a quarter of the Dutch population experiences LBP at any moment in time (Picavet & Schouten, 2003). Besides, LBP has been shown to be recurrent in a majority of patients (Andersson, 1999; Picavet & Schouten, 2003) and it can potentially lead to chronic pain (Kovacs et al., 2005). Because of this high prevalence and its potential to develop into chronicity, LBP can strongly interfere with people's lives as well as with their participation in society. Furthermore, in the working population, LBP has shown to lead to work disability (Eriksen et al., 2004; Matsudaira et al., 2012; Welch et al., 2009), sick leave (Geuskens et al., 2008; van den Heuvel et al., 2004), and early retirement (Costa-Black et al., 2010; Faber et al., 2010; Picavet & Schouten, 2003), indicating a large impact on the working population as well. All the above-mentioned consequences have economic effects that have been highlighted in a recent study estimating the total costs of LBP for Dutch society to be €4.3 Billion in 2007 (which was at that time 0.6% of the gross national product) as a consequence of, among other variables, health costs, production loss, and disability costs (Lambeek et al., 2011). Therefore, it can be concluded that LBP is a major issue in (working) society. In order to better understand the problem of LBP, more knowledge on the causal mechanisms of LBP is needed. This thesis describes a combined epidemiological and biomechanical approach to enhance our understanding of LBP etiology.

WORK-RELATED RISK FACTORS OF LBP

In the past years, epidemiological studies have contributed to our understanding of the etiology of LBP. In certain sectors of industry and in some occupations, the prevalence of LBP is considerably higher than in the general working population (Punnett & Wegman, 2004), indicating some work-relatedness of the etiology of LBP (Lötters et al., 2003). This work-relatedness has become more clear as, besides personal risk factors (e.g. age, smoking habits, physical capacity and body weight; Hamberg-van Reenen et al., 2007; Hooftman et al., 2004; Leboeuf-Yde, 2004; Wai et al., 2008) and (work related) psychosocial risk factors (e.g. stress, social support and job satisfaction, role conflict and job control; Eatough et al., 2012; Hartvigsen et al., 2004; Linton, 2001), the occurrence of LBP has been associated with physical work-related risk factors. Of these physical risk factors, lifting, carrying, pushing, pulling, awkward trunk postures (e.g., flexion and rotation) and whole body vibrations are most frequently reported to be associated with LBP (Chen et al., 2009; da Costa & Vieira, 2010; Griffith et al., 2012; Lis et al., 2007; Lötters et al., 2003). Despite this, other studies have argued that evidence concerning physical risk factors of LBP is weak, possibly as a result of insufficient quality of studies performed thus far (Bakker et al., 2009; Kwon et al., 2011) due to the absence of adequately quantified physical work load in prospective studies. This inconsistency and lack of knowledge has negatively affected the prevention of LBP and has hampered abilities to recommend acceptable levels of biomechanical loads at work (Fallentin et al., 2001). Furthermore, although work-related interventions in attempts to reduce LBP occurrence have frequently been applied (Westgaard & Winkel, 1997), in general, these interventions have not proven to be successful on a large scale (Dempsey, 2007; Verbeek et al., 2011). In part, this may be due to absence or inadequacy of measurements of physical loading.

Failure mechanisms

Despite our lack of knowledge on LBP etiology, several models have been developed to describe the causal chain of the occurrence of LBP (e.g.; Chaffin, 2009; van der Beek & Frings-Dresen, 1998; van Dieën et al., 1999; Wells et al., 2004). All of these models assume mechanical load in the lower back as a result of exposure to physical load at the workplace (i.e., due to the above mentioned risk factors, such as lifting and trunk flexion) to be an important variable in this chain (Figure 1.1). Such mechanical loads (i.e., low-back moments as indicators for mechanical load, or compression and shear forces on the lumbar spine) are in most of these models at, or close to, the end of the causal chain, thereby providing a more direct relationship with spinal failure and consequently with LBP than exposure variables. These mechanical load metrics can therefore provide important insights into the etiology of LBP (Wells et al., 2004). The advantage of the use of mechanical load metrics as opposed to more traditional exposure measures is that different exposures (e.g., lifting, twisting and bending) that can be expressed in three dimensions (i.e., duration, frequency and intensity) affect the same mechanical load (Burdorf, 2010). Besides, the magnitude of exposure variables (i.e., number of lifts or time working in an awkward posture) is not directly related to the magnitude of mechanical load variables. As an example, when lifting a 6kg box, compression forces can be up to 5000N during lifting objects from ground level, but these forces are approximately half this magnitude when the box is lifted from shoulder level (Faber et al., 2009). Moreover, even with no or small loads on the hands, mechanical low-back loading can be substantial, as a result of gravitational forces acting on the upper body and upper extremities as well as due to acceleration of these body segments (van Dieën et al., 2010). Therefore, several exposure variables that can be expressed in terms of frequency, duration and intensity of a lifting task all affect the magnitude of mechanical load on the lower back in a different way (Figure 1.1; Davis & Marras, 2000; Faber et al., 2007; Ferguson et al., 2002; Hoozemans et al., 2008; Marras et al., 1999).

Besides the above, mechanical loads can also take other mediating factors into account. These factors, such as psychosocial factors, personal factors and work-related factors can interact with the abovementioned causal chain in multiple ways (Chaffin, 2009; Wells et al., 2004). As an example, under psychosocial load, workers are more likely to experience more physical strain during work, for instance due to a change in work velocity or work strategy, and this may increase the risk of LBP (Eatough et al., 2012). With regard to personal factors, it has been shown that men may have a higher back load due to a higher torso mass (Hooftman et al., 2004), but also a higher load tolerance than women (Waters et al., 1993). As a final example, the type of job and company are associated with variables like deadlines and workplace culture (Moray, 2000), influencing the way a workers interacts with the environment, which potentially affects the physical load on the worker. From the above, it can be concluded that when measuring mechanical loads rather than crude exposure estimates (i.e., number of lifts, time in a trunk flexed posture), the causality with LBP can be assessed with more accuracy because mediating factors can be taken into account.

Empirical evidence has shown that mechanical load metrics are stronger associated with LBP than exposure estimates (Norman et al., 1998). Therefore, using mechanical load metrics in field settings seems to be important when striving to enhance our understanding on the etiology of LBP (Burdorf, 2010; Wells et al., 2004). However, measurement methods are prone to a trade-off between accuracy and feasibility, in terms of investments in time and costs (Winkel & Mathiassen, 1994). Therefore, in general, with a limited research budget, relatively simple (subjective) observations or self-reports are applied on a larger group of subjects, whereas a more thorough assessment of the work-load often implies that fewer workers can be measured. Moreover, these thorough assessment tools often consist of laboratory-based measurements that are difficult to apply in a field-based setting. This trade-off and the currently available measurement tools will be discussed later in this introduction.

In the studies described in this thesis we assess low back moments at the level of the L5-S1 joint only. Furthermore, we did not separate these moments into shear forces or compression forces. However, we assume that there is a strong correlation of loads among the different levels of the low-back. Furthermore, a strong correlation of low-back moments with shear forces and compression forces has been shown before (van Dieën & Kingma, 2005). Therefore, it is assumed that moments at the level of L5-S1 provide a representative measure of low-back loads in general.

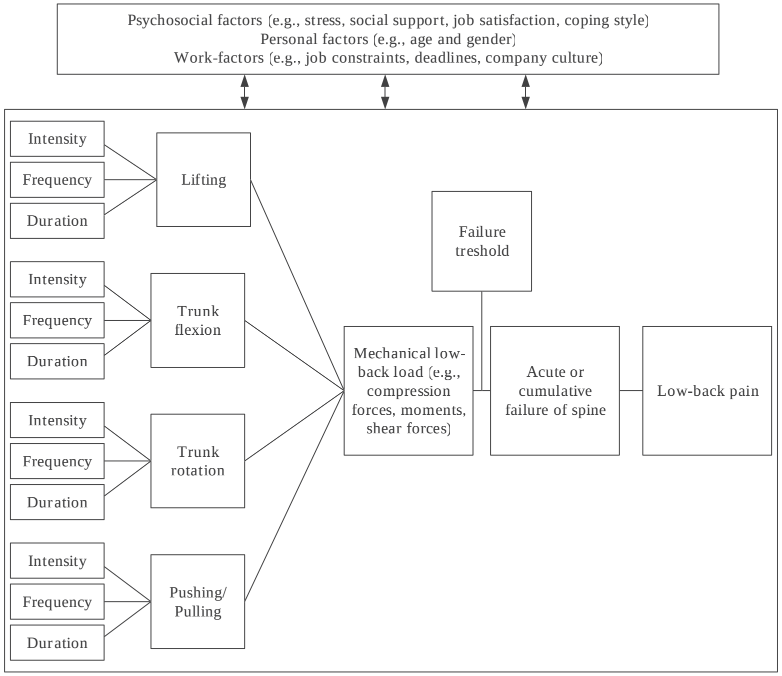

Figure 1.1 | Model representing the association of physical work load and LBP, inspired by other models (Chaffin, 2009; van der Beek & Frings-Dresen, 1998; Wells et al., 2004). Different exposures (i.e., lifting, trunk flexion, trunk rotation and pushing/pulling) that can be expressed in a duration, frequency and intensity are taken into account when measuring a mechanical load (e.g., compression forces on the spine or low-back moments). Subsequently, these mechanical loads can, depending on the failure threshold of the spine, cause failure (either acute or due to cumulative loads) which potentially leads to LBP. These loads furthermore take into account mediating variables of which the effects, for the sake of readability of the figure, are represented in a simplified way. It should be noted that the exposures shown are not independent, as, for example a lifting task usually involves trunk flexion.

The second part of the causal chain for LBP etiology, in which the (mechanical) load eventually leads to the occurrence of LBP, has been discussed in the literature as well (e.g., Adams, 2004; Chaffin, 2009; Marras, 2012). Although a specific cause of LBP is established in only 10% of all LBP cases (Koes et al., 2006), damage to structures of the vertebral column as a result of mechanical loading is a likely cause of LBP (van Dieën et al., 1999; Wang et al., 2012b). In cadaver experiments, damage to several structures of the spinal motion segments (facet joints and inter-vertebral discs, but in most of the cases vertebral endplates) has been shown under several protocols of realistic mechanical loading of spinal motion segments (Adams et al., 1994; Brinckmann et al., 1988; Callaghan & McGill, 2001; Gallagher et al., 2007; Gunning et al., 2001; Howarth & Callaghan, 2012; van Dieën et al., 2006). Moreover, in a retrospective cadaveric study, signs of endplate and disc damage were strongly related to a history of LBP (Wang et al., 2012a, b). From these data, in general, two mechanisms for the occurrence of failure can be derived. The first mechanism assumes damage of spinal structures due to acute high loads, causing instantaneous failure of tissue (Figure 1.2, upper panel). This mechanism is supported by studies reporting instantaneously high loads causing damage to spinal structures (Howarth & Callaghan, 2012), in most cases failure of the spinal endplate (Adams et al., 1994; Brinckmann et al., 1988). However, not just a single supra-maximal compression but also repeated sub-maximal compression can lead to injury. This repeated sub-maximal compression causes similar damage at lower force levels (Brinckmann et al., 1988; Hansson et al., 1987). Therefore, the second mechanism supposes an accumulation of micro-damage, decreasing the tolerance of tissue and eventually leading to failure after sustained or repeated loading (Figure 1.2, lower panel).

The above mentioned in-vitro studies, showing that peak and cumulative loads may cause spinal failure, militate in favor of both the peak as well as the cumulative etiological mechanism. However, this information is based on in-vitro studies, which bring along some limitations. For example, it is known that there is no one-to-one relationship between mechanical damage to the spine and the actual occurrence of LBP (Wang et al., 2012a, b). Besides, cadaver material does recover poorly from loads as biological repair is absent (van der Veen et al., 2005). The abovementioned studies on cumulative loading should therefore be interpreted with caution as damage in these studies might have occurred earlier than during *in-vivo* conditions. On the other hand, the opposite, underestimation of cumulative load effects in *in-vitro* studies, also cannot be excluded. Specifically, alternative explanations for cumulative load effects are not taken into account in *in-vitro* studies. Such alternative explanations for the cumulative etiological mechanism are impaired coordination due to neuromuscular or cardiovascular fatigue after cumulative loading. It has been suggested that this impaired coordination might cause a reduction of the tolerance of the spine due to lack of stability (Granata & Gottipati, 2008; Johanson et al., 2011; Sparto et al., 1997) or alterations in work postures posing higher loads on the spine (Bonato et al., 2003; Dolan & Adams, 1998).

From the above, it can be concluded that epidemiological studies in which peak and cumulative mechanical load and LBP are assessed *in-vivo* in work settings should be considered in order to obtain more information on the etiology of LBP. Marras and colleagues investigated the predictive value of a variety of low-back load parameters for the risk of LBP (2010; 1995). Other studies suggest that cumulative loads acting on the spine may contribute to LBP (Kerr et al., 2001; Kumar, 1990; Neumann et al., 2001a; Norman et al., 1998) as well as to specific lower back pathologies (i.e., lumbar disc disease; Seidler et al., 2009; Seidler et al., 2003). Other studies showed evidence for the association of peak loads and LBP (Kerr et al., 2001; Neumann et al., 2001a; Norman et al., 1998; Punnett et al., 1991). However, the above-mentioned studies describe either cross-sectional studies or prospective studies with low-back loads that are based on crude estimates. Risk associations that are based on prospective studies are more valid for obtaining insight into etiological causalities as the occurrence of LBP follows the exposure to a certain risk factor. Therefore, these designs are more preferable in epidemiological studies (Rothman & Greenland, 2005). However, to the best of our knowledge, information on mechanical loads on the lower back and the occurrences of LBP from such prospective studies is not available. Two important reasons for this void are the lack of field-based measurement techniques to determine mechanical loads on the low-back, and the lack of knowledge on the variability of physical load and thus on the type of measurement allocation (e.g., measuring multiple workers, a few times or a few workers multiple times) needed. Caveats and potential possibilities in measurement strategies of epidemiological studies considering these two factors will therefore be discussed in the following paragraphs.

ASSESSMENT OF PHYSICAL WORK LOAD

An important reason for the inconsistency of information on LBP etiology is that risk associations are highly influenced by the choice of a measurement method (Burdorf, 2010; David, 2005). Measurement methods are prone to a trade-off between accuracy and feasibility (in terms of investments in time and costs) and the available resources determine the precision of a measurement and hence, statistical efficiency (Mathiassen & Bolin, 2011). In order to enhance our knowledge on the etiology of LBP it seems to be relevant, as stated in the previous paragraphs, to assess mechanical load metrics rather than exposure estimates. However, as accurate measurement tools to assess these mechanical loads are often difficult to apply to field situations, concessions with respect to the quality of measurement techniques are often made. As a result, many studies measure exposure variables rather than mechanical load.

Work-related risk factors can be assessed by either self-reports, observations (i.e. subjective risk estimations or structured observations) or direct measurements (e.g. muscle activity measurements, goniometry and measurement of external forces). These methods have been discussed in the literature and advantages and disadvantages have been evaluated (David, 2005; van der Beek & Frings-Dresen, 1998). Self-reports have been used in numerous epidemiological studies and are easily applicable; however, their accuracy has been questioned (Balogh et al., 2004; Punnett, 2004). Therefore, in contrast to epidemiological studies, self-reports of workload are rarely used for evaluation in ergonomic practice (Hansson et al., 2001).

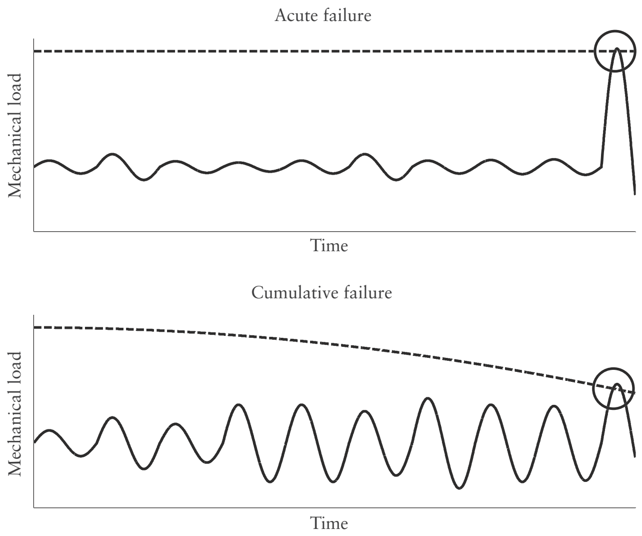

Figure 1.2 | Illustration of spinal motion segment failure due to either a single acute loading event (upper panel) or cyclic loading leading to cumulative fatigue failure (lower panel). In both figures, the mechanical loading pattern is represented with a solid line whereas the failure threshold of the spine is represented with a dashed line. In the event of a large acute loading, a single load can reach the failure threshold. During a cyclic loading pattern the repeated load lowers the threshold, eventually leading to failure at a smaller load level. The figure is inspired by earlier work (Chaffin, 2009; Marras, 2012; McGill, 2009).

Instead, risk estimates by observers are more frequent used. Although these observations have a higher accuracy and validity than self-reports, their accuracy and validity is assumed to be lower than that of direct measurement tools (Spielholz et al., 2001; Takala et al., 2010). Accuracy is limited because risk estimations are often based on crude categorization. Validity is limited because of the difficulty for the assessors to conduct such measurements objectively. Structured observations performed by observers might not be so vulnerable for subjectivity. However, these observations are just as the risk estimations, prone to limited accuracy as they are often based on crude categorization (de Looze et al., 1994a; van Wyk et al., 2009). This inaccuracy has been shown to lead to large errors when used as input in biomechanical models to estimate mechanical low-back load (de Looze et al., 1994b). Ultimately, observational methods often lack a clear quantification of physical load in the dimension of duration, frequency and magnitude (Takala et al., 2010).

The last group of measurement tools is the group of direct measurements. These measurements are assumed to be the most objective and thus the most valid and have the ability to provide mechanical load estimates. For instance, it has been shown that mechanical low-back load can be measured accurately by using inverse dynamic linked-segment models, which combine information from three-dimensional motion tracking procedures and external force measurements (e.g., Kingma et al., 1996; Kingma et al., 2010; Plamondon et al., 1996). However, such measurements are time and money consuming. In addition, they can hardly be used outside the laboratory setting as they strongly interfere with the work performed which highly complicates measurements of realistic occupational situations. Furthermore, it is known that when mock-ups of field situations are made in a laboratory setting, workers tend to execute tasks differently than they would have done in the actual field (Faber et al., 2011). Therefore, laboratory measurements tools are, despite their high accuracy and internal validity not always externally valid.

Accordingly, research has focused on less costly (with respect to time and money) low-back load assessment methods, which can be brought into the work place easily. For example, variables serving as a proxy for mechanical load are often adopted, such as muscle activity measures (Hägg et al., 2000), static position measures (i.e., load distances; Potvin, 1997; van Dieën et al., 2010) or measures obtained from instrumented motion monitors (e.g., Marras et al., 2007; Marras et al., 2010). Despite the fact that some of these estimates are closely correlated to mechanical low-back load (Neumann et al., 2001b), it is believed that mechanical low-back load estimates are needed to properly assess the load on the low-back (Wells et al., 2004). Video-based methods using postural exposure data in biomechanical models to calculate mechanical low-back loads have been shown to be a promising category of techniques (Chang et al., 2010; Norman et al., 1998; Potvin, 1997; Sutherland et al., 2008) to assess low-back load metrics such as static (Neumann et al., 2001b), cumulative (Sutherland et al., 2008) or peak low-back moments (Norman et al., 1998). These methods allow raters with minimal training and minor use of equipment to collect occupational low-back load data with high inter-rater agreement (Cann et al., 2008; Sullivan et al., 2002). However, these methods have rarely been implemented in field-based epidemiological studies. Therefore, improving such measurement tools (in terms of validity, reliability and feasibility) should be considered, which is another focus of this thesis.

VARIABILITY IN PHYSICAL WORK LOAD

Another important aspect to be considered when constructing a measurement strategy for physical risk factors of LBP is the variability (between and within workers) of physical risk factors (either expressed in exposure metrics or in mechanical loads). This variability should be considered in the planning, analysis and interpretation of epidemiologic studies as inadequate distribution of measurements can lead to biased regression results (Tielemans et al., 1998) and to a reduced statistical power (Mathiassen et al., 2002; Mathiassen et al., 2003). Therefore, measurement occasions should be distributed adequately over subjects, time and tasks groups (Loomis & Kromhout, 2004).

Statistical consequences of work load variability between individuals, and within and between days within individuals have been addressed in several studies for various load metrics and occupational settings (e.g., Hansson et al., 2006; Svendsen et al., 2005; Wahlstrom et al., 2010). The effect of sample size on the variance of the load estimate has been discussed, including the number of samples to arrive at a sufficiently reliable load estimate (Allread et al., 2000; Paquet et al., 2005; Svendsen et al., 2005). It has been shown that although the reliability of a measurement improves when more subjects are sampled or when load is measured over multiple occasions, with increasing sample size, the load estimate improves less when measuring more subjects (Mathiassen et al., 2002; Mathiassen et al., 2003). Other studies discuss several options for collecting data from workers (sample allocation). For example, it has been shown that it might be more beneficial to collect data over multiple days from multiple workers rather than to collect data from just a few workers on a single day (Liv et al., 2010; Svendsen et al., 2005). Also the effects of group-based measurement approaches, that are often adopted (e.g., Ariëns et al., 2001; Burdorf & Jansen, 2006), have been described frequently. In these approaches, workers are classified into groups; work load is measured only in a selection of workers within each group, and the (mean) group-based work load of the measured workers is assigned to all subjects in the group. Work load-outcome relationships are then determined using these load estimates together with individual outcome data (LBP) from all subjects. These group-based measurement approaches have proven to be successful for the assessment of workloads during several occupational tasks (Hoozemans et al., 2001; Paquet et al., 2005). Furthermore, stronger associations have been found in a group-based approach compared to an individual-based approach when it comes to associations of physical load to outcomes (Jansen & Burdorf, 2003).

From the above, it can be concluded that there is quite some knowledge available on how to deal with variability in physical work load. Also the effect of sampling strategies and study protocols (e.g., group-based measurement approaches) on the reliability of measured physical risk factors has been discussed thoroughly. However, information on the effect of this variability on statistical power of eventual risk associations is limited. This is therefore an additional focus of the present thesis.

AIMS AND OUTLINE OF THE THESIS

From the previous paragraphs it can be concluded that insufficient knowledge on the linkage of biomechanical loading and the etiology of LBP is available. More specifically, limited information on the effect of mechanical low-back load on LBP has been obtained from prospective epidemiological studies. This is partly because study properties that highly affect the risk associations (e.g., data sampling, the exact load metric used etc.) are insufficiently understood. Another reason is the limited availability of occupational assessment tools that are easily applicable in field based situations. From these hiatuses, four principle aims that will be addressed in this thesis are formulated.

In this thesis we aim to assess:

1. The predictive value for LBP of mechanical loads as compared to (subjective) exposure estimates
2. The effects of methodological issues on the predictive value of low-back load metrics for the occurrence of LBP
3. The applicability of video-based quantification of mechanical low-back load in a field situation

These three aims will be instrumental for our main aim, to gain insight into:

4. The etiology of LBP using mechanical load metrics

These principle aims will be addressed in the chapters of the thesis according to the following outline.

The predictive value for LBP of mechanical loads as compared to (subjective) exposure estimates

As mechanical low-back loads have been assumed to have a higher predictive value than exposures (obtained from self-reports or from observations) for LBP, our initial goal was to test this hypothesis in a prospective study. In Chapter 2, a study is described in which the predictive value of subjective observer assessments for the risk of musculoskeletal pain is evaluated. Results of this study can be used to assess the quality of these subjective metrics. In Chapter 3, a study is described in which, based on video observation, a first attempt was made to obtain a mechanical load metric in a prospective epidemiological study. In this study, mechanical loads were assessed with static calculations of mechanical back load based on crude posture observation categories. The association with LBP of the mechanical load metric studied in this chapter was assessed and was compared to associations of exposure estimates that are generally adopted as exposure risk factors. These studies provide information on the predictive value of mechanical low-back load metrics in comparison to exposure metrics (determined either subjectively or from observations).

The effects of methodological issues on the predictive value of low-back loads for LBP
Previously, cumulative load has often been suggested to be a potential risk factor of LBP. As peak loads are also assumed to be independent risk factors of LBP, the question arises how repeated peaks should be weighted in cumulative load calculations. Chapter 4 describes an analysis based on in-vitro data. In this analysis, the contribution of repetition of peaks in the calculation of cumulative loads was assessed. Data from this study may provide important information for future studies assessing cumulative low-back load as a risk factor of LBP.

The statistical power of studies assessing risk factors of LBP is highly influenced by the measurement strategies used. However, in physical load-outcome associations this influence is poorly understood. Therefore, a simulation study assessing the effect of several measurement strategies on the predictive value of such risk associations has been performed (Chapter 5). Data from this study can provide useful information for the design of future epidemiological studies.

The applicability of video based quantification of mechanical low-back load in a field situation
As described above, measuring mechanical low-back loads in work field settings is a daunting task as current measurement methods often interfere with the work or provide only crude estimates. Therefore, a video analysis method for the assessment of low-back loads in the field was developed. As opposed to the earlier used method of mechanical load calculation based on crude posture observations (Chapter 3), this method consists of a detailed kinematic analysis of manual material handling tasks. This analysis method can potentially be used in ergonomic practice and future epidemiological studies as it copes with abovementioned drawbacks. In order to test the quality of this method, at first, the validity of the method was tested by comparing it to a gold-standard laboratory method. The proposed video analysis method is described in detail in Chapter 6, in which also the outcomes of this validation-test are provided. Also the inter-rater reliability of the video analysis method applied to actual field situations is assessed (Chapter 7). Results of both studies provide information on the applicability of the described method in future research and in ergonomic practice.

The etiology of LBP using mechanical load metrics
The earlier mentioned video analysis method was applied in a large prospective cohort study. Results from this study are described in Chapter 8, providing insight in LBP etiology that can be useful for future prevention of LBP.

In the epilogue (Chapter 9), an overview of the studies described above will be provided. At the end of this chapter, final conclusions of this thesis will be drawn. Furthermore, implications for ergonomics practice and future research will be discussed.