Chapter 9

Epilogue

THESIS SUMMARY

Physical work load is considered an important risk factor for low-back pain (LBP). However, in **Chapter 1** it is also argued that reported associations between physical workload and LBP are rather inconsistent. This inconsistency is a barrier for the understanding of the etiology of LBP. One reason for this lack of knowledge may be inadequate quantifications of mechanical loads in work situations. It was argued that, in most models for LBP etiology, these mechanical loads (i.e., loads at the level of the lower back, for example, low-back moments as indicators for mechanical load, or compression or shear forces on the lumbar spine) are at the end of the causal chain, thereby providing a rather direct relationship with spinal damage. Different exposures (e.g., lifting, twisting and bending) affect the same mechanical load, so that mechanical load can be considered a 'final common pathway' to spine injury. Therefore, obtaining mechanical load metrics in prospective studies seems to be important when striving to obtain more understanding of the etiology of LBP. However, such studies are lacking, probably because of the absence of occupational assessment tools that are easily applicable in field situations. Furthermore, also other measurement issues that affect the outcome of such risk associations are insufficiently understood. Therefore, four aims were addressed in the current thesis. The main findings regarding these aims will be discussed in the following sub-paragraphs. Subsequently, general conclusions will be drawn based on this thesis, and future directions for research and ergonomic practice will be discussed.

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

As mechanical low-back loads have been assumed to be more predictive for LBP than exposures (i.e., obtained from self-reports or from observations), our initial goal was to test this hypothesis in a prospective cohort study. Data presented in **Chapter 2** show that although trained observers were able to predict neck and shoulder pain, they could not predict LBP well. This can be explained by the fact that compared to neck and shoulder load, low-back load depends on a larger number of task variables (i.e. trunk posture, arm posture, load magnitude and load distance) that seem to be difficult to assess subjectively. The finding that risk estimates of LBP are not significantly associated with LBP prevalence questions the accuracy of these subjective risk estimates and advocates for the use of precise measurements rather than estimates.

From the findings reported in **Chapter 3**, we can conclude that cumulative mechanical low-back load, as obtained from calculations of mechanical back load based on posture observation, is a significant predictor of LBP. Moreover, it was shown that this mechanical load metric has a stronger association with LBP than earlier reported exposure risk factors (i.e., time in a flexed position and number of lifts during a working day). These findings support our hypothesis that a mechanical low-back load measure provides a stronger association with LBP than exposure measures. Based on these results it seems justified to develop more precise methods to assess mechanical loads at the workplace. Furthermore, mechanical load variables should be considered in future epidemiological studies to obtain more information on LBP etiology.

The effects of methodological issues on the predictive value of low-back loads for LBP

As a second step towards a better understanding of the LBP etiology we assessed the impact of some methodological issues that are of importance in epidemiological studies on the matter. In cumulative mechanical loads, the (peak) low-back load magnitude of a given work task is often multiplied by the number of load cycles of that particular task, while these multiplications of all tasks during a work shift are summed. However, it has been argued that high forces have more impact on the increase in failure risk than a high number of cycles. **Chapter 4** confirms this hypothesis by a re-analysis of in-vitro mechanical loading to failure data. This analysis showed that weighting compression forces and number of load cycles with exponents of 2 and 0.2, respectively, provides the best prediction of in vitro lumbar spine failure following cumulative loading. This non-linear load-failure association has implications for future studies assessing the effect of cumulative low-back loading for investigation of LBP etiology.

Another methodological issue that we have assessed is the effect of group size in group-based measurement protocols on the statistical power of eventual risk associations (**Chapter 5**). In group-based measurement protocols, workers are grouped according to common characteristics, such as their work tasks. Group-averaged exposure estimates are assigned to all workers in the group on the basis of data measured in a subgroup only, while outcome data (i.e., LBP) are assessed for all workers. Such protocols are often used in epidemiological studies on physical risk factors of LBP. Our results show that the power in such a group-based study depends more on the total number of workers included in the study (using individual outcome data on LBP) than on the size of the subpopulation from which exposures are obtained. Effectively, in order to reach a power of more than 0.80 at a p-level of <0.05, in general, at least 30 workers have to be included in each task group, with exposure measurements of at least 5 of these workers. When exposure was observed from fewer than 5 workers, the odds ratio (OR) of the exposure-outcome relationship was negatively biased. Therefore, findings suggest that although exposure of sufficient workers (≥5) should be assessed in order to avoid bias of the OR, it seems to be more efficient to assess LBP from a larger number of workers (≥30 per task group).

The applicability of video based quantification of mechanical low-back load in a field situation

Measuring mechanical low-back loads in field settings is a tempting task, as current measurement methods often interfere with the employer's work or only crude metrics are used. Therefore, a video analysis method for the assessment of mechanical low-back loads in the field was developed, based on earlier work. This analysis method can potentially be used in ergonomics practice and in future epidemiological studies as video material can be collected without interfering with the worker's tasks. **Chapter 6** describes a study in which this video analysis method for the assessment of low-back moments during occupational lifting was validated by performing a comparison with a laboratory reference method. No overall differences in peak and mean moments between the reference method and the video analysis methods were found and intra-class correlation coefficients (ICCs) revealed a strong correspondence of the video analysis method and the reference method. In **Chapter 7**, the inter-rater reliability of the video analysis method was tested on video material that had been recorded in field settings. Results from this chapter show excellent agreement among raters (ICC >0.9), while inter-rater variation was relatively low (<10 Nm), for low-back moment estimates of peak and mean moments. However, occasional substantial errors were shown during the assessment of manual material handling (MMH) tasks. These errors appeared to result from amplification of random posture rating errors in tasks of short duration, especially in MMH tasks that are difficult to rate because they were filmed from a non-sagittal view. Despite these errors, it can be concluded that the current video analysis method is valid as well as reliable. The latter is also the case when assessing occupational field tasks.

The etiology of LBP using mechanical load metrics

In the final study described in this thesis (**Chapter 8**), the video analysis method was applied to a large prospective cohort. Mechanical loads were assessed and their association with LBP was estimated. This study shows that cumulative mechanical low-back loads predict LBP. However, the required exponential weighting of force level appeared to be lower than predicted from the in-vitro data analyzed in Chapter 4. Nevertheless, these findings are in favor of the mechanism for the etiology of LBP described in Chapter 1, where cumulative loads play an important role in the cause of LBP, potentially as a result of accumulation of micro-damage, and/or through impaired coordination due to fatigue. As peak loads are not significantly associated with LBP, instantaneous tissue failure due to peak loads on the spine is a less probable cause of LBP based on the current data. However, the latter mechanism for etiology cannot be ruled out, especially as our data suggest that a weighting of load magnitude with a power larger than 1 in calculations of cumulative loads provided a better fit to our data.

GENERAL DISCUSSION

A number of general conclusions can be drawn from the current thesis. First of all, regarding the predictive value for LBP, a clear advantage was shown for the use of mechanical load metrics over exposures obtained by subjective assessments or structured posture observation. This is in line with data from a cross-sectional study (Norman et al., 1998) and with several models arguing that mechanical loads (i.e., loads at the level of the lower back, such as compression forces on the lumbar spine or low-back moments) are at the end of the causal chain and thus provide a more direct relationship with spinal failure and consequently with LBP (Chaffin, 2009; Marras, 2012). This direct relation stems from the fact that these mechanical loads can provide information on duration, frequency and intensity of multiple exposures. Quantification of exposures (i.e., number of lifts or time working in an awkward posture) is not directly related to the quantification of mechanical load variables. Furthermore, mechanical loads also take other mediating factors into account such as psychosocial factors, personal factors and work-related factors (as discussed in Chapter 1). Because of the arguments above, in the present thesis, mechanical loads were considered in order to obtain more information on LBP etiology. In this section the most important sources of error in quantifying low-back load with the methods used in this thesis, and their implications, will be discussed.

The use of posture observations in biomechanical models

Mechanical loads can be obtained by combining information from measured hand forces and structured posture observations in a biomechanical model, as often used in epidemiological studies. Such mechanical loads are predictive for LBP, as has been described in Chapter 3. However, this chapter describes only a first attempt to quantify low-back mechanical load in a prospective study. It has been shown before that using observational data as input for a biomechanical calculation, can lead to large inaccuracies (de Looze et al., 1994b). These inaccuracies can be illustrated by some simple examples based on data of the study described in Chapter 3. In these examples, a static procedure is used, estimating low-back moments from the moments caused by the gravitational force on the upper body with respect to the low-back and of the moments caused by the external force on the hands with respect to the low-back. Let us consider two causes of errors in back load estimates based on the observation of MMH tasks: inaccuracy due to crude categorization of the trunk flexion angle and misclassification of a MMH task. Consider a MMH task that is rated by an observer as being performed in a trunk flexion category ranging from 30 to 60°. When comparing two lifting tasks in which a 15 kg load is lifted with the arms downward and the trunk in the extremes within this category (30 or 60° flexion), moment arms of the upper body and the external force on the hands can differ considerably between these extremes. With 30° trunk flexion, the moment arms of the upper body and de hands are about 20 cm and 30 cm, respectively. However, during 60°

trunk flexion, these values increase to approximately 35 cm and 50 cm, respectively. When performing a static calculation of the low-back moment in these two situations, moments are estimated to be about 125 Nm and 215 Nm, for the 30° and 60° trunk flexion angle respectively (Table 9.1).

Another type of inaccuracy stems from errors in classifying the type of MMH task. Therefore, as a second example we consider a lifting task in which a 25kg load (equivalent to an external force measured at the hands of approximately 250N) is lifted, with the arms downward and the trunk in 30° of flexion. This force, applied at the hands in combination with the gravitational force of the upper body can contribute to a moment at the low-back of 155Nm. However, when this lifting task is incorrectly classified as being a pushing MMH task, the direction of the force vector representing the external force at the hands rotates over 90°. This can lead to a corresponding moment arm that is rather small and can even be in opposite direction relative to the moment arm corresponding to the upper body gravitational force. The moment at the lower back due to these two tasks can therefore differ considerably between these tasks, being about 155Nm and 55Nm for a lifting and a pushing task, respectively (Table 9.1).

Measuring low-back load using a video analysis method

When combining the results from Chapters 6 and 7 on the validity and reliability of our video analysis method with the considerations in the previous paragraph, it becomes clear that the video analysis method is more accurate than the method of static back load estimation based on observational data as used in Chapter 3. The video model has been shown to be applicable in the field, thereby not interfering with the worker's tasks, while measuring in laboratory settings can lead to measuring unrealistic work situations (Faber et al., 2011). Furthermore, moments were obtained from a dynamical analysis, taking not only the contribution of gravitation to the moments, but also the angular and linear acceleration of segments, into account. Our data show that this led to an improvement of the accuracy (Chapter 6) which is in line with earlier studies showing an underestimation of approximately ten percent when ignoring movement dynamics (van Dieën et al., 2010). Furthermore, several studies have reported on the problem of assessing movement outside the sagittal plane due to projection biases (e.g., Kingma et al., 1998). With the current model we decreased this source of error since we allowed for axial rotation of the manikin and quasi-three-dimensional movements (i.e., trunk rotation, trunk lateral flexion and arm abduction). The validity of this approach was supported by the fact that errors were not larger in asymmetric MMH tasks compared to symmetric MMH tasks (Chapter 6). Finally, with the present method we tried to overcome the error made by crude categorization of segment orientations, which can lead to relatively large errors, as has been shown in literature (de Looze et al., 1994b; van Wyk et al., 2009) and in Table 9.1 of this epilogue. Chapters 6 & 7 show that the video method used is both valid when compared to a laboratory gold standard and reliable among raters when used in a field setting.

Table 9.1 | Numerical example showing the consequence of inaccuracies due to the use of crude observational categories of the trunk flexion angle (upper part) and of misclassification of the type of MMH (lower part). Low-back moments were calculated by summing the moment caused by the gravitational force on the upper body with respect to the low-back and the moments caused by the external force on the hands with respect to the low-back (static procedure). The mass of the upper body is assumed to be 40kg and gravitational acceleration was estimated at $10m/s^{2.}$

	Inaccuracy in observation of trunk angle			
	Lifting 15 kg (30° trunk flexion)		Lifting 15 kg (60° trunk flexion)	
	Force F=m·a	Moment M=d·F	Force F=m·a	Moment M=d·F
Gravitational force upper body	40·10=400N	400·0.20=80Nm	40·10=400N	400·0.35=140Nm
Force measured at the hands	15·10=150N	150·0.30=45Nm	15·10=150N	150·0.50=75Nm
Total		122Nm		215Nm
	Inaccuracy in classification of the type of MMH			
	Lifting 25 kg (30° trunk flexion)		Pushing 25 kg (30° trunk flexion)	
	Force F=m·a	Moment M =d·F	Force F=m·a	Moment M=d·F
Gravitational force upper body	40·10=400N	400·0.20=80Nm	40·10=400N	400·0.20=80Nm
Force measured at the hands	25·10=250N	250·0.30=75Nm	250N	250·-0.10=-25Nm
Total		155 Nm		55Nm

We found rather small (<10%) non-systematic, random errors for peak and mean low-back moments when compared to a gold standard or when compared among raters. However, between-rater differences showed some occasional inaccuracies up to 45Nm (for peak moments) and 40Nm (for mean moments). Although these values are much smaller than the errors as shown in Table 9.1, this method may thus have some inaccuracy. One reason may be that modeling the entire trunk in two segments might not provide an accurate representation of the trunk curvature (Lariviere & Gagnon, 1999). Furthermore, both chapters showed relatively large inaccuracy in the dynamic component of the moment, which may partly be due to the interpolation between the four key data points. In addition, in tasks of short duration, random errors are strongly amplified due to double differentiation of position data. Therefore, interpolation or posture prediction algorithms can be assessed in future studies to improve interpolation accuracy. Using interpolation algorithms might additionally help to reduce analysis time.

Predictive values of mechanical low-back loads

In our data, we could not see a higher predictive value of mechanical loads obtained from the more accurate video analysis method as compared to mechanical loads calculated from observation postures. Inaccuracies as described in Table 9.1 are expected to bias the predictive value of posture observation-based estimation of mechanical load for LBP, as it is known that large inaccuracy leads to biased risk associations (Tielemans et al., 1998) and a reduced statistical power (Mathiassen et al., 2002; Mathiassen & Paquet, 2010). Assessment methods that are more accurate are therefore assumed to have a higher power when assessing associations with LBP. However, in practice this is not always the case in epidemiological literature (Griffith et al., 2012), as studies that measure more accurately often measure insufficient numbers of workers, which reduces the power of the study. Therefore, in an additional analysis we tested the effect of back load estimation accuracy by comparing the calculation of mechanical loads based on observations in Chapter 3 of this thesis to mechanical loads assessed more accurately using video analysis as described in Chapter 8. In the same population (as has been described in detail in Chapter 8), mechanical peak and cumulative loads were calculated as obtained from both methods. For individual largest peak moments, Pearson's correlation coefficients showed a poor correlation between these two methods (r=0.48). Differences between the two methods up to 200Nm can be seen (Figure 9.1). Based on the examples in Table 9.1, such differences are not unexpected and are probably mainly due to errors in the posture observation based method. It can therefore be concluded that, although mechanical loads are preferable over exposure metrics when assessing LBP etiology, mechanical loads can contain substantial inaccuracies, especially when observational data are used as input for a biomechanical model. However, these data also show that when individual peak loads are calculated on a group level, higher agreement (r=0.82) between the two methods is found. The video analysis method that we developed was expected to be more accurate. Therefore, as an additional analysis, we compared the predictive value of these two approaches. For both approaches, group-based mechanical load estimates were assessed (obtained from the group of workers from whom video analysis were performed; n=93) and were assigned to all tasks group members (those workers from whom LBP data in at least one of the three years of follow-up are available; n=1131). In this procedure, LBP was defined when a worker reported regular or prolonged LBP during at least one of the three years of follow-up. Crude risk associations were estimated by calculating ORs, 95% confidence intervals and p-values with the load (as continuous variables) being the independent variable and LBP (either case or control) being the dependent variable using logistic regression. From these results it can be concluded that, whereas relatively large differences exist between the two metrics for peak moment (on an individual level; Figure 9.1), both metrics show comparable predictive values for LBP (when group-based mechanical loads are used; Table 9.2). This may partly be caused by the fact that, although the two moments differ considerably on an individual level, these individual variations are diminished when calculating group-based estimates. This is in line with earlier studies that have shown high within-subject variability as compared to between-subject variability in a task group (Allread et al., 2000; Paquet et al., 2005). Measuring multiple subjects at separate occasions and assigning group-based load variables to all group members (as we have done here) is therefore an efficient way to reduce this variance, providing a stable metric that leads to stronger associations with LBP than individual metrics (Jansen & Burdorf, 2003). This implies that an improvement in the accuracy of assessments of a mechanical load on an individual level does not necessarily lead to a more predictive metric on a group level.

For cumulative loads, it was shown that both methods have a higher agreement on an individual level as shown by the relatively high correlation coefficients (r=0.87; Figure 9.1). Group-based mechanical load values agree even more among the two methods (r=0.96), which led to comparable predictive values for LBP for the two estimates of mechanical load (Table 9.2). A reason for this might be that random errors as a result of high inaccuracy in observations as input in a biomechanical model are diminished when calculating cumulative loads. This is at least partly caused by the fact that cumulative loads are based on roughly an hour of observation whereas peak loads occur just in a fraction of this measurement time. Another cause is the fact that, our video analysis method was used only for MMH tasks and mechanical loads during the periods in which no MMH tasks were performed are based on the same observational data in both estimates. This effect of small differences in predictive value for the two estimates is even more diminished when calculating group-based mechanical load. Considering the above, it can be questioned whether a large investment (in term of money and time) for measurements of physical work load is worth the effort. An answer to this question can be deducted from data presented in Chapter 5 clearly showing that at a certain point, it is more beneficial to include more workers in a study to collect LBP outcomes from than more workers to collect exposure data from. When exposure is measured from a sufficient number of workers (≥5 workers per task group), measuring exposure of more workers does not necessarily lead to higher powered risk associations.

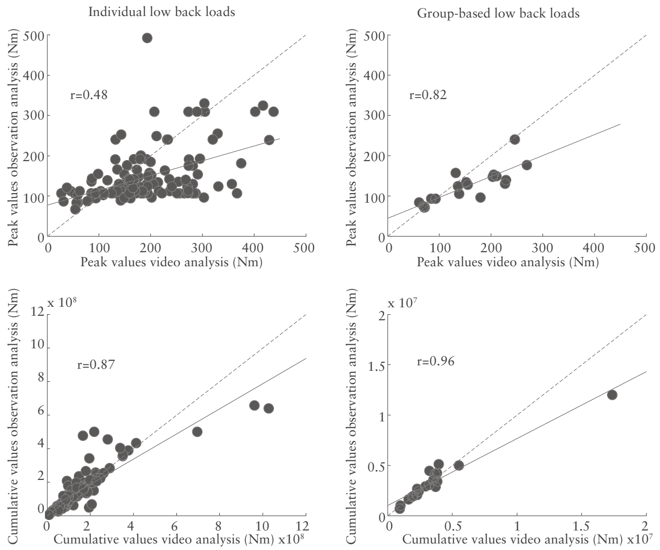

Figure 9.1 | Scatter plot depicting the association of mechanical loads as obtained from structured observational data used in a biomechanical model (Chapter 3 of this thesis; y-axis) and moments obtained from the video analysis method (Chapter 8 of this thesis; x-axis). Peak loads (upper panels) as well as cumulative loads (lower panels) on an individual level (left panels) and on a group level (right panels) are shown. The best fit through the data points (solid line) as well as the x=y reference line (dashed line) are shown. Also, Pearson's correlation coefficients are shown, depicting the correlation between the two methods of calculation of moments.

Non-linear association of low-back load and LBP

Based on several findings presented in this thesis, it can be speculated that there may be a non-linear association between low-back load and LBP. A first finding is that peak loads should be weighted higher when calculating cumulative loads. This is in accordance with data from earlier studies suggesting that that high forces have a more important impact on the increase in risk of failure than the duration of the load (Brinckmann et al., 1988; Hansson et al., 1987; Rapillard et al., 2006). According to this assumption, 15 cycles of 2000N load are presumed to be likely to cause a higher risk of damage than 20 cycles of 1500N. Therefore, multiple non-linear models for the association of mechanical load and LBP have been suggested.

Table 9.2 | Predictive value of peak and cumulative mechanical loads for the occurrence of LBP. Mean moments with standard deviations (Std), ORs, 95% CIs and levels of significance are shown for moments based on a biomechanical model using crude observational variables as input (data from Chapter 3) and moments obtained from a more accurate video analysis method (Chapter 8).

		LBP	No LBP		
Moments	Chapter	Mean (Std)	Mean (Std)	OR (95% CI)	p-value
Peak	Chapter 8	142.35(65.55)	134.82(61.25)	1.002(1.000-1.004)	0.047
Peak	Chapter 3	117.72(40.17)	113.66(36.42)	1.003(1.000-1.006)	0.076
Cumulative	Chapter 8	$1.25\cdot10^{8}(1.24\cdot10^{8})$	$1.05\cdot10^{8}(0.56\cdot10^{8})$	1.003(1.001-1.004)	0.001
Cumulative	Chapter 3	$1.17\cdot10^{8}(8.63\cdot10^{8)}$	$1.03\cdot10^{8}(0.47\cdot10^{8})$	1.003(1.001-1.005)	0.001

For example, second order (Seidler et al., 2009; Seidler et al., 2003), fourth order weighting of load magnitude (Jäger et al., 2000), polynomial calculated cumulative load (Parkinson & Callaghan, 2007) or low-pass filtered loading (Krajcarski & Wells, 2008). Our findings show that weighting compression forces and number of load cycles with exponents of approximately 2 and 0.2, respectively, provides a suitable metric for prediction of in vitro failure due to cumulative loading (Chapter 4), which is in line with these suggestions. Therefore, cumulative loads containing weighting were expected to be better predictors for LBP. However, although squared cumulative loads tended to have a better fit than linearly weighted cumulative loads (Chapter 8), differences between these two metrics were marginal. A potential reason might be the lack of discriminating power in the current data. Despite the fact that we showed that in-vitro failure of spine segments during repeated loading at a constant load levels is best predicted when using a tenth power of load level (Chapter 4), this metric was not significantly associated with LBP in our epidemiological data (Chapter 8). Data from Chapter 4 were based on a mechanical load protocol applied on in-vitro material. On the one hand, in-vitro material lacks the potential to repair micro-damage, which would cause an overestimation of the importance of the loading frequency. On the other hand, in-vitro testing does not take into account that the risk of low-back injury may increase when respiratory or neuromuscular fatigue causes impaired coordination (Brereton & McGill, 1999; Janssens et al., 2010; Sparto et al., 1997; van Dieën et al., 1998), leading to an underestimation of the importance of the temporal characteristics of loading. As we show here that squared weighted load is, but load weighted to the tenth power is not associated to LBP, the latter characteristic of in-vivo conditions may play an important role here. However, this reasoning may be premature as the lack of predictive value of the tenth power weighting might also be a result of the fact that the metric becomes highly affected by inaccuracies in the measurements or actual variation in the work pattern. This can also be deduced from Chapter 8 showing that the association of this metric to LBP is very non-robust (Chapter 8). Finally, the suggested non-linearity can also be deducted from Figures 9.1 & 9.2 as it can be hypothesized that associations are likely caused by a relatively small group of workers that experience high mechanical loads and report a high prevalence of LBP, while the majority of workers are in task groups experiencing moderate low-back load and average LBP prevalence. This is in line with the non-linear association of physical work load and LBP that has been suggested before (e.g., McGill, 2009). Non-linear models, as have been discussed already in the past (e.g., Jansen & Burdorf, 2003) can therefore be considered when assessing such risk associations.

An additional simulation procedure was conducted in which the effect of the presence of certain groups in the data-set was assessed. In order to do so (based on the earlier described cohort in Chapter 8, with 19 task groups and with LBP assessed in 1131 subjects and mechanical load assessed in 93 subjects), all 19 task groups were consecutively left out of the cohort using a Jack-knife procedure (Chen et al., 2004; Efron & Gong, 1983). For each virtual study in which one of the groups was left out, logistic regressions were conducted using the peak and cumulative loads consecutively as continuous independent variables and LBP as the dichotomous dependent variable. ORs and p-values were calculated in each virtual study. Results show that, when leaving the group with the highest low-back load out of the cohort although ORs remain above 1, significant associations of both cumulative and peak loads disappear (Figure 9.2). This shows the importance of the presence of high mechanical loads in a cohort.

Etiology of LBP

Despite the limitations discussed above, it was shown in this thesis (Chapters 3 & 8) that cumulative low-back loads are highly predictive for the occurrence of LBP. These findings are in line with earlier studies (Kumar, 1990; Neumann et al., 2001a; Norman et al., 1998). Although peak loads have been shown to be significantly associated with LBP as well in earlier studies (Marras et al., 2010; Neumann et al., 2001a; Norman et al., 1998), this could not be confirmed in this thesis. Therefore, with respect to the etiology of LBP, our findings provide stronger support for a mechanism of LBP etiology due to cumulative loads than for a mechanism based on single peak loads. Such an etiological mechanism based on cumulative load might result from the occurrence of LBP as a consequence of injury or tissue responses due to accumulation of micro-damage or through impaired coordination due to neuromuscular or respiratory fatigue.

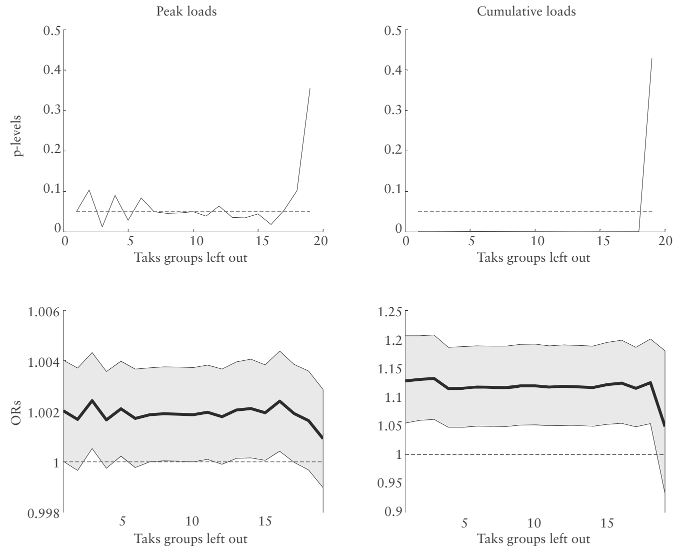

Figure 9.2 | Jack-knife leaving one task group out analysis after which risk associations were calculated. Risk associations were calculated for peak loads (left panels) and cumulative loads (right panels) showing the p-values (upper panels) and ORs and 95% confidence intervals (lower panels) of the associations. Task groups were ranked by magnitude of the mechanical load with group 1 being the group with the lowest mechanical load and group 19 being the group with the highest work load.

Chapter 8 shows a trend of the association of peak loads and LBP. It should be noted that the accuracy of a maximal peak load in an individual is lower than that of a cumulative load, thereby negatively affecting power. The fact that we could not prove the association of peak load to LBP therefore does not prove the absence of this effect. Furthermore, as it was shown in Chapter 8 that including the weighting of peaks in calculations of cumulative loads improves the predictive value for such cumulative loads, peaks should be taken into account. Finally, associations of peak loads and LBP have been shown in earlier studies (Marras et al., 2010; Neumann et al., 2001a; Norman et al., 1998).

DIRECTIONS FOR FUTURE RESEARCH AND ERGONOMIC PRACTICE

Although cumulative load has been shown to be predictive of LBP in this thesis, the exact underlying causal mechanism remains unknown. As an example, more research is needed on the contribution of peak loads on the development of LBP. Although valid and reliable mechanical loads were obtained using the present video analysis method, no substantial improvements in the predictive value were shown relative to observation-based estimation of mechanical loads. With the video assessment tool introduced here, only MMH tasks can be assessed and relatively large occasional errors were shown when using the method. Measurement tools that are able to obtain continuous accurate information on physical work load are therefore required. Several research groups have been working on ambulatory measurement systems that can be used in the field, using goniometers and ultrasonic systems to track body postures (Freitag et al., 2007; Glitsch et al., 2007; Marras et al., 2010). However, these devices are rather bulky and heavy, limiting workers in performing their work which hamper valid work load measurements. Potentially, more easily applicable methods can be found in the direction of ambulatory measurements tools using, for example wireless inertial sensors (Faber et al., 2009a; Faber et al., 2010c) in combination with instrumented force-shoes (Faber et al., 2010b). Also more sophisticated hardware using marker less motion tracking can be used in future studies (e.g., using devices such as Microsoft Kinect; Dutta, 2012). These methods have a low interference with the workers' tasks and allow for collection of large amounts of accurate data. Once these methods have been proven to be applicable in field measurements, they can be used on a larger scale to continuously monitor low-back loading in an epidemiological study.

A second direction for future research is to assess the non-linear association of low-back load and LBP. Although not convincingly demonstrated to be better than linear weighting in Chapter 8, a non-linear association of mechanical low-back load and LBP might be superior to linear weighting of mechanical loads in calculations of cumulative loads. One reason is that, as shown in Chapter 8, squared weighting showed a slightly better fit than linear weighting. Furthermore, it was shown in this epilogue that small task groups experiencing high low-back loads and having a high LBP prevalence play an important role in the calculation of risk associations. Finally, the analyses of in vitro data in Chapter 4 favored a non-linear weighting. Therefore, more research in the direction of modeling risk associations is necessary in order to improve the knowledge on LBP etiology. Furthermore, such non-linear models might be of importance to establish directives for physical work load. Current knowledge lacks the ability to recommend acceptable levels of biomechanical work load (Fallentin et al., 2001).

A final aspect that has shown to be important in this thesis is the variation (within and between subjects) that plays a role in the assessment of physical work load. It was shown that the choice of a measurement strategy (e.g., the size of a sample, allocation of a sample and the use of group vs. individual based load estimates) plays in important role in the assessment of physical work load. Therefore, in future epidemiological studies, assessment strategies should be analyzed a priori, using estimates of relevant variance components (Mathiassen, 2006). Furthermore, also monetary information (such as unit costs, and cost function shapes) could play a role here and should play a role in decisions on measurement strategies (Mathiassen & Bolin, 2011).

Concerning the implications of the present findings for ergonomic practice, it has been shown that cumulative loads are associated with the occurrence of back pain. Therefore, it might be of importance to target prevention on the reduction of cumulative loads. These loads are for a share caused by handling of heavy loads, working in awkward body postures (i.e., working in a trunk flexed posture combined with trunk rotation and large load distances with respect to the low-back) and working in unsafe environments.

As peaks play an important role in the weighting of cumulative loads, such loads should not be overlooked. As an example, these peaks loads can be caused by high low-back loads as a result of handling of heavy loads in awkward postures (i.e., working in a trunk flexed posture combined with trunk rotation and large load distances with respect to the low-back) in a high pace (i.e., causing high body accelerations). Prevention should thus be targeted based on these work situations and peak mechanical loads should be avoided by reducing low-back loads during MMH tasks.