Towards ambulatory assessment of spinal loading in the field

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Chapter 9

Epilogue

Thesis overview and discussion

In the general introduction (**chapter 1**) an overview was given of the literature providing the basis for this thesis. Recent studies reported that low back pain (LBP) is still a significant medical as well as an economic burden to western society. Epidemiological studies have shown that LBP has a multifactorial origin. Personal (e.g. age, gender), psychosocial (e.g. job satisfaction and job control) as well as physical (e.g. manual lifting and awkward postures) risk factors have been shown to be related to LBP. Of the physical risk factors, manual lifting and working in a flexed posture have been shown to be most strongly related to LBP. This is probably because these tasks result in high mechanical loading of the spine. Therefore, manual lifting tasks, which often involve trunk flexion, have frequently been studied in laboratory settings, for instance to investigate the effect of different aspects of manual lifting (e.g. initial object position, object size and lifting technique) on spinal loading.

Generalisability of results of typical laboratory studies

The first two studies described in this thesis (chapters 2 & 3) investigated whether the results of typical laboratory studies regarding the effects of ergonomic interventions on spinal loading, can directly be generalised to the field. In the first study (**chapter 2**), we investigated the effects of ergonomic interventions involving a reduction of the mass and an increase in the initial lifting height of building blocks in a mock-up of an industrial depalletising task. In contrast with most laboratory studies, the lifting task was performed by experienced (construction) workers who were free to lift the building blocks the way they usually do at the workplace. No lifting speed was imposed and the construction workers were free to use preferred foot placement. Furthermore, for each of the 6 lifting conditions (3 block masses X 2 lifting heights), multiple building blocks were positioned in a row, thereby varying the initial horizontal block position. Construction workers were asked to keep on removing building blocks, until they would normally prefer to walk around to the other side of the pallet or step on the pallet. In this way, participants were free to choose the maximal initial horizontal position they lifted the building blocks from, for each of the 6 lifting conditions independently. The results of this study showed that the construction workers changed their lifting

behaviour depending on the lifting condition, mostly in such a way that the effect of the ergonomic interventions would be attenuated. For example, when block mass was reduced or the lifting height was increased, construction workers choose to lift blocks from further horizontal distances, thereby reducing the expected effects of the ergonomic interventions on spinal loading. In addition, a surprising finding of this study was that, in contrast with previously reported laboratory studies, no effect of initial horizontal object position on spinal loading was found for lifting blocks from near the ground level (from the pallet). It was unclear whether this was due to differences between the studies in the type of lifting tasks used or due to the lifting experience of the subjects. Therefore, another study was designed to investigate the effects of the type of lifting task and lifting experience on spinal loading. In a laboratory experiment a group of inexperienced subjects performed lifts from close and far initial horizontal positions (**chapter 3**). Subjects first performed those lifts in a typical laboratory lifting task in which they simply lifted a box until an upright body posture was attained, i.e., 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 they could use (e.g. shifting and tilting). After this short familiarisation training, the now "experienced" subjects repeated the more realistic lifting task including box transport. In line with previous laboratory studies, we found a significant effect of initial horizontal position on spinal loading for the typical laboratory lifting task without box transport. Furthermore, in accordance with the results of the study presented in chapter 2, no effect of initial horizontal position on spinal loading was found in the more realistic lifting task that was performed after familiarisation training. The disappearance of the effect of the initial horizontal position on spinal loading was shown to be caused by the type of lifting task as well as the lifting experience of the subjects.

In conclusion, the two studies summarised above indicated that typical laboratory studies cannot simply be generalised to the field: the effects of ergonomic interventions were shown to be dependent on the type of lifting task performed as well as on the experience of the subject with the specific task. Therefore, based on

these studies, it was recommended to measure the effect of ergonomic interventions in the actual work environment using experienced subjects.

Application of two currently available measurement methods to assess spinal loading in the field

Based on the first two studies it was recommended to investigate the effects of ergonomic interventions at the workplace using experienced subjects. Therefore, two field studies were conducted, each applying another currently available method to assess spinal loading.

The first field study (**chapter 4**), investigated the effects of ship motion on peak spinal loading during manual lifting. All measurements were done on a ship at sea. For the assessment of spinal loading, we installed our standard laboratory measurement system (i.e. force plate and optoelectronic and EMG measurement systems) in the lunchroom of a training vessel of the Royal Netherlands Navy. Furthermore, ship motion was measured using a ship motion measurement unit containing accelerometers and gyroscopes. Ship motion data was used as independent variable and as additional input to the biomechanical model that was applied to calculate spinal loading. Subjects, experienced with working on a ship, performed 1-min trials consisting of 5 lifts, which were repeated over a wide range of sailing conditions. To investigate whether people time their lifts in order to reduce the effect of ship motion on spinal loading, trials were performed at a free and at a constrained (lifting every 10s) work pace. The results of this study showed small but significant effects of ship motion on spinal loading. Furthermore, lifting at a free work pace instead of a constrained work pace did not reduce the effect of ship motion on spinal loading.

In the second field study (**chapter 5**) a much more simple method was applied to assess 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 building 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 the static spinal loading (static worksite method). Outcomes of the static worksite method were compared to the outcomes of the laboratory study reported in chapter 2 using a "state of the art" dynamic analysis

of the spinal loading (dynamic laboratory method). This comparison showed that the static worksite method underestimated spinal loading by on average 20%, which appeared to be mainly caused by ignoring the dynamics of the lifting task. Furthermore, this underestimation varied over lifting conditions, which makes it difficult to correct for this error. However, because the differences in spinal loading between lifting conditions were large, ordering of tasks based on spinal loading was consistent between methods. Thus, the static worksite method seems to be a valid tool to assess the effects of ergonomic interventions on spinal loading as long as these are substantial.

Although both measurement methods were successfully applied in the field, some limitations should be mentioned. A disadvantage of the laboratory measurement method, as applied in the first field study, was that it was a very expensive enterprise to transport the laboratory equipment to the ship and install it in the field setting. Furthermore, although measurements were carried out in the field, subjects still could not perform the exact work they usually do on a ship because lifts had to be performed on the force platform within the field of view of the optoelectronic cameras. Although the measurement method applied in the second field study did allow the assessment of the specific lifting task that the subjects usually do during a normal workday, the movement pattern of the subjects was still constrained because, when tape-measures were obtained, subjects had to stand still. Another disadvantage of this measurement method is, as mentioned before, that the loading caused by dynamics in the lifting tasks is neglected, which makes it unsuitable for studies such as the first field study. Furthermore, if measurements have to be performed over a longer period of time, the measurement method becomes very labour intensive. An important limitation of both measurement methods is that the outcomes of the measurements can be affected by an observation-induced bias (Hawthorne effect): people behaving differently when aware of being watched. This could especially be a problem in ergonomic intervention studies in which subject often know what the goal of the intervention is. To overcome these limitations, alternative measurement methods are needed. In the last section of this thesis (see summary below), new ambulatory measurement techniques have been explored which are being developed to bypass these limitations.

Development of new ambulatory measurement tools for the assessment of spinal loading in the field.

To overcome the limitations of the measurement methods encountered in the two field studies described above and in the measure methods applied in epidemiological studies (based on video analysis) described in the general introduction it was concluded that new methods should be developed. In the last section of this thesis we explored the application of two recently developed body mounted measurement techniques, which could be used to assess spinal loading: inertial/magnetic sensors (IMSs) which could be used instead of an optoelectronic system to measure kinematics of body segments and instrumented force shoes (FSs) which could be used instead of force plates to measure 3D ground reaction forces. In contrast with the measurement techniques used in the field studies described in chapters 4 and 5, these new body mounted techniques allow subjects to perform their work in a more or less unconstrained way. Furthermore, observation bias will be a smaller problem, since the presence of external observers (i.e. cameras or experimenters) is not required during the measurements. Especially when future developments in the measurement techniques allow for whole-day measurements, subjects will probably forget that their actions are being recorded and act in a more natural way. Although some previous studies have reported on the technical validation of the IMSs and FSs measurement systems, none have attempted to obtain measures of spinal loading using these new measurement techniques. Therefore, the last 3 studies presented in this thesis explored the potential of these new techniques to obtain measures of spinal loading.

Because trunk inclination is an important determinant of spinal loading, in **chapter 6** we tested a simple method to measure trunk inclination using a single IMS placed on the trunk segment. Since the trunk is not a rigid segment, the magnitude of the measured trunk inclination is dependent on the location on the back at which the inclination is measured. Therefore, the aim of this study was to find the optimal location on the back of an IMS for measurement of trunk inclination. The degree of trunk inclination is related to spinal loading because of its effect on the moment arm of the trunk centre of mass. Therefore, the gold standard reference for trunk inclination, measured with an optoelectronic system,

was defined as the angle between the vertical and the line trough the L5/S1 joint and the combined centre of mass of the abdomen, thorax and head. Because most of the trunk flexion takes place in the lumbar spine, we found that the optimal sensor placement was fairly low: at about 25% of the distance from the sacrum to the C7 spinous process.

A more complete estimate of the spinal loading can be obtained if also external forces are taken into account. When external forces are measured at the hands a top-down inverse-dynamics analysis can be applied and when external forces are measured at the feet, a bottom-up inverse-dynamics analysis can be applied. Because force measurements at the hands are not very practical in field settings, we choose to explore the use of a bottom-up analysis measuring external forces at the feet using FSs. In **chapter 7,** a technical validation study was presented in which the performance of FSs in assessing ground reaction forces (GRFs) and resulting bottom-up calculated ankle and L5/S1 moments was investigated in 19 different lifting, pushing & pulling and walking tasks. In this experiment, kinematics (position and orientation) of the lower body segments and of the FSs were recorded with an optoelectronic system and not with IMSs, because the aim of this study was to purely test the precision of the FSs. Precision of the FS system was assessed by comparing the outcomes of the FS measurements with the outcomes of synchronously collected force plate (FP) measurements. In general, good agreement between the FS and FP measurements were found.

In the FS validation study summarised above, kinematics of the segments and the FSs were measured by an optoelectronic system. Alternatively, in field measurements IMSs could be utilised to measure kinematics of lower body segments and FSs, so that a bottom-up analysis of joint moments can be performed. Because IMS can measure orientation of segments only, the positions of segments relative to each other and relative to the GRFs have to be determined by linking them, assuming fixed segment lengths and zero joint translation. These assumptions will result in errors in joint position and moments, and those errors will accumulate over segments in the analysis. In **chapter 8,** a study was described that investigated the effect of using segment orientations only (orientation based method) instead of using orientations and positions (reference method) on lower body joint moments. To purely test the effect of analysis methods (and not measurement methods), GRFs and segment positions and/or orientations used in

both analyses were measured using the same measurement systems: a FP and optoelectronic marker clusters. Three different lifting techniques were studied to test whether the amount of knee flexion would affect the discrepancy between the two analysis methods. Outcomes of this study showed that the difference between the two analysis methods remained small for the knee moments but for the hip and L5/S1 moments, the differences were more substantial especially when more knee flexion was involved.

In conclusion, in chapter 6 an easy applicable method was established for the measurement of trunk inclination with a single IMS. In chapters 7 and 8, the first steps were taken towards ambulatory dynamic bottom-up estimation of spinal loading utilising FSs to measure GRFs and IMSs to measure segment kinematics. Errors originating from different components of the proposed measurement system have been investigated separately: errors due to measuring GRF with FSs instead of FPs and errors due to using segment orientation only instead of segment orientation plus position. Future studies have to be carried out to determine the validity of the complete ambulatory measurement system. In the last part of this general discussion, recommendations for such future studies will be provided.

Directions for future research

As mentioned in the general introduction, most of the epidemiologic studies that have investigated the relationship between spinal loading and LBP had significant limitations in quantification of back loading, which might be a reason that a number of studies did not find significant associations. Furthermore, based on the studies described in chapters 2 and 3 it was concluded that it would be better to measure the effect of ergonomic interventions in the field rather than in the laboratory, since the effects of interventions were shown to be dependent on the type of task performed and on experience with the specific lifting task. A number of studies have investigated the effect of ergonomic interventions in the field (Elders et al., 2000; Lötters & Burdof, 2002; van der Molen et al., 2005; Bos et al., 2006; Dawson et al., 2007; Williams et al., 2007; Martimo et al., 2008; Rivilis et al., 2008; Bigos et al., 2009; van Oostrom et al., 2009). However, almost none of these studies assessed the effect of the ergonomic interventions on spinal loading.

Instead, these intervention studies mainly focused on the effects of the intervention on health outcomes (e.g. LBP incidence). Therefore, in the studies showing no effect on health outcome, it is unknown whether the intervention did not have effect due to the lack of an effect on spinal loading or due to the absence of a causal relation between health outcome and spinal loading. Conversely, for the studies with positive effects on health outcome, it cannot be ascertained that this was due to reduced spinal loading. Therefore, reviews on the effect of ergonomic interventions on LBP concluded that not only the changes health outcomes should be measured but also the changes in mechanical exposure (Lötters & Burdof, 2002; van der Molen et al., 2005).

As mentioned earlier, an important reason that in most of the above discussed (large scale) epidemiologic and ergonomic intervention studies failed to sufficiently quantify spinal loading is probably that available methods for objective assessment spinal loading (e.g. video analysis) are labour intensive and therefore expensive. Therefore, the objective of the last 3 studies of this thesis was to develop automated ambulatory measurement tools, which do not have this limitation, because directly measured and digitally recorded data are available immediately after the measurement.

The first study showed that trunk inclination could be measured with good accuracy when placing a single IMS on the trunk and this method is ready to be used in future field studies. To get an estimate of the effect of trunk inclination on spinal loading, the trunk inclination could be further used to estimate spinal moments due to static trunk posture when using this trunk inclination as input to a simple biomechanical model. When including accelerometer and gyroscope data (which are also measured by an IMS) in such a biomechanical model, the dynamic component of spinal loading due to trunk motion could additionally be estimated. Future studies should be carried out to investigate how well (static + dynamic) spinal loading can be estimated using a single IMS on the back.

The goal of the next two chapters was to develop ambulatory measurement techniques allowing easy assessment of the total spinal loading (including external forces) in the field. To this end, first steps were taken in the development of a system using a bottom-up linked-segment inverse dynamic approach based on FSs and IMSs. One important source of error in such a measurement system that has not been touched upon in this thesis is the "anatomical calibration" procedure that

has to be performed when measuring with IMS: relating the IMS coordinate system to the coordinate system of the corresponding body segment. This anatomical calibration is not straightforward when measuring with IMSs because no position data are available (O'Donovan et al., 2007; Picerno et al., 2008; Favre et al., 2009; Cutti et al., 2010). Future studies should investigate the magnitude of errors in joint positions and moments caused by errors in anatomical calibration. Another source of error that has not been dealt with in this thesis is the error due to imperfect orientation measurement with the IMSs. Although inclination can be measured with a high accuracy with IMSs, the orientation around the vertical axis can contain substantial errors, especially near ferromagnetic materials such as a force plate (Roetenberg et al., 2005; de Vries et al., 2009). If a summation of all these errors will lead to unacceptably high errors in estimated spinal loading, errors might be reduced by incorporating a recently developed body mounted system that can track positions of IMSs with reasonable accuracy using a 3D magnetic actuator (Roetenberg et al., 2007; Schepers et al., 2010). However, a disadvantage of this system is that, up to date, the 3D magnetic actuator is not small enough to be worn underneath the clothes.

An alternative to the bottom-up approach described above could be a top-down approach, which might allow estimation of spinal moments with a higher accuracy since magnetic disturbances are usually smaller higher above floor level. Furthermore, a recent study showed that errors in the relative pelvis-trunk orientation due to magnetic disturbances can be corrected by using additional information measured by a potentiometer (relative twist angle) connecting the pelvis and trunk IMSs (Plamondon et al., 2007). Two other research groups should be mentioned that (Freitag et al., 2007; Glitsch et al., 2007; Marras et al., 2010) have developed a body mounted ambulatory measurement systems to record upper body motion, using measurement techniques that are insensitive to magnetic disturbances (e.g. goniometers, 3D ultrasonic system to track hand location). A limitation of these systems, however, is that they are fairly heavy and bulky so that they cannot be worn underneath the clothes, which could constrain the natural motion pattern. An additional limitation of a top- down approach, and the main reason why we chose to start with studying a bottom-up approach, is that a top-down analysis of spinal moments requires external forces exerted by the hands as input, of which direct measurement is not very practical in the field

(Marras et al., 2010) . Alternative ways of estimating hand forces could be the aim of future studies. For instance, external forces at the hand could be calculated by starting with the GRFs measured by the FSs and subsequently subtract the forces due to gravity and linear acceleration of all body segments measured by the IMSs.

Conclusion

The main objective of this thesis was to bring the study of back loading during tasks such as manual lifting from the laboratory setting to the field. Based on the results of previous epidemiological literature and the first four studies described in this thesis, it was concluded that results from typical laboratory studies cannot be generalised directly to the field and that there is a need for automated ambulatory measurement tools that allow for easy and continuous assessment of spinal loading in the field. The last part of the thesis focused on the development of such measurement tools. One simple tool studied in this thesis, using a single IMS to measure trunk inclination, is ready to be applied in the field setting. In addition, first steps were made towards the development of a measurement system that allows a more complete assessment of spinal loading (including dynamics and external forces). However, before this measurement system can be applied in the field, further validation studies are required.