Biomechanical evaluation of exoskeletons for the prevention of Low-Back Pain

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Summary

Real-time assessment of L5-S1 moments, an application for trunk exoskeletons.

In the first two Chapters, steps were taken to investigate the accuracy of an ambulatory low back load monitoring system applicable for being used in conjunction with a trunk exoskeleton. In **Chapter 2**, an ambulatory monitoring system (Force shoes + Inertial measurement units) was used to estimate 3D hand forces. During lifting, hand force errors were low (10-15 N RMSD), with around 30% of the error due to the ambulatory measurement equipment. In **Chapter 3**, the estimated hand forces were used to calculate L5-S1 flexion/extension moments using a top-down method during symmetrical lifting. In this study, GRF's were measured with force plates, instead of force shoes. In addition, the number of inertial measurement units was systematically reduced, to end up with the minimum number of sensors needed for accurate moment estimation. In addition, the effect of neglecting the horizontal components of the GRF was investigated. These steps were taken in order to optimize the practical usability of the monitoring system by minimizing the required number of sensors. Results showed that with six IMU's (Pelvis, Trunk, Upper arms & Forearms) and only the vertical component of the GRF, RMS errors of the L5-S1 flexion/extension moments were below 18 Nm. The fact that the horizontal component of the GRF can be omitted, opens up the possibility to use pressure insoles. These horizontal forces are difficult if not impossible to measure accurately using pressure insoles. Neglecting the horizontal component of the GRF will lead to an overestimation of the L5-S1 moment, because during lifting the load is always slightly pulled towards the lifter. In addition, L5-S1 moment estimates could be improved by improving the capturing of shoulder translation.

Design and evaluation of passive trunk exoskeletons

In **Chapters 4-7**, the focus was on passive trunk exoskeletons with the aim to reduce mechanical loading of the low back, in order to reduce the risk of development of LBP. In **Chapter 4**, the effect of a commercially available passive trunk exoskeleton on back and abdominal muscle activation, hip and lumbar flexion and on the contribution of both the human and the exoskeleton to the L5-S1 net moment during static bending at

five different hand heights was assessed. Two configurations of the exoskeleton (LOW & HIGH), differing in angle-torque characteristics, were tested. For the evaluation of the exoskeletons a lab-based system, instead of the ambulatory system tested in Chapters 2 & 3, was used to precisely determine the effects of the exoskeleton. L5-S1 moments generated by the subjects were significantly reduced (15–20% for the most effective type) at all hand heights. Significant reductions (11–57%) in back muscle activity were found compared to WITHOUT for both exoskeletons for some conditions. However, EMG reductions compared to WITHOUT were highly variable across subjects and not always significant. The device allowed for substantial lumbar bending (up to 70°) so that a number of participants showed the flexion-relaxation phenomenon, which prevented further reduction of back EMG by the device and even resulted in an increase in abdominal activity at low hand positions. In **Chapter 5**, the same trunk exoskeleton was tested but now during lifting from knee and ankle height from a near and far horizontal position, with a load of 10 kg. In addition, the effect of the exoskeleton on the L5-S1 compression force was investigated. The peak L5-S1 compression force was reduced by around 5–10% for lifts from the FAR position for both KNEE and ANKLE height lifts. Subjects did adjust their lifting style when wearing the device, resulting in a 17% reduced peak trunk angular velocity and 5 degrees increased lumbar flexion, especially during ANKLE height lifts. In **Chapter 6**, a novel passive trunk exoskeleton was designed and preliminarily tested. The exoskeleton included several mechanisms, such as sliders, misalignment compensation, and bendable beams at the back, that were intended to enhance the versatility of the device. Both the biomechanical and the functional aspects of the trunk exoskeleton were assessed. Compared to a rigid back structure, an increase of more than 25% range of motion of the trunk in the sagittal plane was observed by using the flexible beams of the novel trunk exoskeleton. Questionnaires showed that participants perceived the exoskeleton as less hindering in almost all tested tasks compared to the passive trunk exoskeleton tested in **Chapters 4 & 5**. In **Chapter 7**, the novel trunk exoskeleton was biomechanically tested during static bending and lifting with various lifting techniques, similarly to **Chapters 4 & 5**. For static bending, the exoskeleton reduced the compression force by 13-21% depending on bending angle. Another positive effect of the exoskeleton was that participants substantially reduced lumbar flexion. While lifting, the exoskeleton reduced the peak compression force, on average, by 14%. Lifting technique did not modify the effect of the exoskeleton such that the reduction in compression force was similar between the three different lifting techniques.

Design and evaluation of active trunk exoskeletons

In **Chapters 8 & 9**, the focus was shifted towards active trunk exoskeletons with the aim to reduce mechanical loading. **Chapter 8** addressed the challenge on how to control an active exoskeleton prototype aimed at reducing compressive low-back loads. An analysis of the biomechanics of lifting tasks revealed two key factors that largely determine low-back loads: the upper body flexion and the load lifted. For each factor, a suitable control strategy for the exoskeleton was implemented. The first control strategy was based on user posture and modulated the support of the exoskeleton based on inclination of the trunk, which is directly related to the moment at the low back induced by gravitational forces on the upper body. The second control strategy was based on detection of hand force needed to lift an object, using electromyography of the forearm muscles. A third strategy was devised as a combination of the first two. The resulting data highlighted that the strategies modulate the assistance as intended by design, i.e., they effectively adjust the commanded assistive torque during operation based on user posture and external mass. The experiment also provided evidence of significant reduction in muscular activity at the lumbar spine (around 30%) associated with using the exoskeleton. In **Chapter 9**, a more extensive analysis was performed based on the same experiment. L5-S1 compression time-series were analyzed to investigate which control strategy would be most effective in reducing low back loading, and whether this was dependent on lifting technique. Peak compression forces substantially decreased when wearing the EXO compared to NO EXO. However, this reduction was partly, by about one third, attributable to a reduction in peak lifting speed, by about 25%, when wearing the EXO. While subtle differences in back load patterns were seen between the three control modes, no differences in peak compression forces were found. In part, this may be related to limitations in the torque generating capacity of the EXO. Therefore, with the current limitations of the motors it was impossible to determine which of the control modes was best. Despite these limitations, the EXO still reduced both peak and cumulative compression forces by about 18%.